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Improving the Flexural Strength of Bowed Marble Panels through Mechanical Treatment

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Abstract
This research examined the conservation options for thin marble cladding as used in Post War architecture in the United States. The phenomenon of bowed marble panels was studied as early as the 1910s, and literature on the topic became more prolific in the 1990s following early catastrophic failures of entire Post War building façades less than 20 years after construction due to little knowledge of material properties. The current hypothesis is that thin marble panels deform due to the disaggregation of calcite grains from environmental hysteresis. Prominent case studies include the Amoco Building in Chicago and Finlandia Hall in Helsinki, with the more historical example of the bowed marble enclosure tablets of New Orleans' above-ground cemeteries. Replacement is the current conservation strategy, which compromises the aesthetics of the marble, and comes at a huge monetary cost. This is detrimental to the historic fabric, especially as the buildings constructed in this era reach 50 years, making them eligible for the National Register of Historic Places. The research presented investigated methods to stabilize and strengthen deformed marble panels where preservation of existing historic fabric is the preferred mode of treatment. Through an examination of the literature of the mechanical reinforcement of concrete slabs and masonry panels, a method to improve the flexural strength of bowed marble panels can be developed and tested through the procedures outlined in Nordtest Method: NT BUILD 499, testing for bowing potential, and ASTM C880-98, testing flexural strength.

Keywords
bowed marble panels, environmental hysteresis, Post War architecture, calcite, mechanical treatment

Disciplines
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INCREASING THE FLEXURAL STRENGTH OF BOWED MARBLE PANELS THROUGH MECHANICAL TREATMENT

Danielle Marie Pape

A THESIS

in

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CHAPTER 1: INTRODUCTION

1.1 Thesis Statement and Purpose

The purpose of this thesis is to examine the conservation options for thin marble cladding as used in Post War architecture in the United States. As its use increased, these veneer panels became thinner to reduce material cost. It was soon discovered that the thin marble panels deformed under certain conditions, including high humidity and temperatures, and failed when improperly secured to the building. Although the deformation mechanism of environmental hysteresis has been recently studied, proposed treatments have focused on panel replacement. The research in this thesis instead investigates methods to stabilize and strengthen deformed marble panels where preservation of existing historic fabric is the preferred mode of treatment.

1.2 Use of Marble as a Building Veneer

The use of thin marble panels as a building veneer was first introduced in the early 1950s and rose in popularity through the 1980s for mid and high-rise curtain wall construction (Scheffler and Gerns 1995, 171). Construction using thin stone panels became more standardized in the 1960s; publications by the Marble Institute of America and the National Association of Marble Producers guided this process.[1] By minimizing the size of

[1] The National Association of Marble Dealers, founded in 1907, merged with the National Association of Marble Producers in 1944 to form the Marble Institute of America. The companies produce publications to raise awareness in the marble industry about the best use of natural stone. In the 1960s, the companies produced the *Marble Engineering Handbook* and *Marble-Faced Precast Panels* as a way to inform the wider building community about the use of thin marble panels.

the panels, often only 1.25 to 1.5 inches thick, the weight was transferred to the structural frame of the building.[2] The aesthetics of the marble panels, along with the "assumed durability qualities" and the ease of "reinforced concrete and steel skeleton frame buildings" led developers to use these thinner panels without understanding the bowing potential of marble when installed as exterior cladding (Cohen and Monteiro 1991, 113). Subsequently, many major buildings experienced severe and dangerous bowing of the façade stone panels. Well-known failures include the Amoco Building in Chicago, Finlandia Hall in Helsinki, and Richmond City Hall in Richmond, Virginia (Grelk et. al 2007, 106).

A curtain wall is defined as "an exterior building wall made of non-load bearing panels that are supported on a structural frame. The curtain wall spans between floors and transfers lateral loads, such as those produced by winds, to the structural frame, while the structural frame alone carries these horizontal as well as gravity loads" (Kelley and Johnson 1998, 77). In relation, a thin stone panel is defined as "stone that is cut to less than 2 inches thick and applied to a building façade in a non-load bearing manner" Scheffler and Gerns 1995, 168). Its origins can be traced to the glass exhibition pavilions of the late 19th

[2] Thin stone veneer has been defined as a panel that has been cut to less than 2 inches thick since the 1960s (*Marble Engineering Handbook* 1962, 21). *Sweet's Architectural Catalogues*, in 1932, defined "modern veneer" as a stone less than 4 inches thick (Scheffler and Gerns 1995, 168). The added thickness of a stone veneer versus a thin stone veneer makes thin stone veneers – used mainly following the 1950s – more likely to be affected by thermal hysteresis.

century, and the masonry infilled metal frame skyscrapers designed by the Chicago School in the 1880s (Kelley and Johnson 1998, 77).

Figure 1 and Figure 2: The Hallidie Building (left), constructed in 1918, in San Francisco (Source: Library of Congress) and the Reliance Building (right), constructed in 1895, in Chicago (Source: Library of Congress). Both buildings represent technological innovations of their time.

The first pure curtain wall constructed building in North America was the Hallidie Building in San Francisco (fig. 1) designed by James Polk in 1918 (Brock 2005, 89-90), while Burnham and Root's Reliance Building in Chicago (fig. 2), constructed in 1895, had 2 to 4 inch stone panels on the exterior of the first two floors and terra cotta paneling for the upper stories (Scheffler and Gerns 1995, 168). Stone panels began to be incorporated into curtain wall construction in the early 1930s, and gained acceptance as a cladding material in the late 1930s; early examples include the Rule-Page Building in Mason City,

Iowa (Hansen and Waggoner, 1940) and the Federal Reserve Bank in Detroit (Smith, Hinchman and Grylls, 1950) (Scheffler and Gerns 1995, 168). There are examples of thin stone panel clad buildings from the 1950s, but prominent buildings were not clad in thin stone until the 1960s (Scheffler and Gerns 1995, 168). The United Nations Secretariat Building, constructed in 1952, is clad in both glass and thin marble panels (Ripple 2012, 15). The use of thin stone panels as cladding was controlled by the quickly evolving technological processes of cutting the panels, as well as the reduced costs of the panels as the thickness decreased. In this time-period, building owners still saw stone as a representation of quality and success, increasing the material's continued usage.

In the 1960s, commercial-grade diamond cutting blades were invented that made it possible to easily cut marble slabs into standardized panel thicknesses (Lewis 1995, 18). Early thin stone panels were made using an advanced reciprocating gang saw process, which was described by the National Building Granite Quarries Association in an advertisement from 1932 (Scheffler and Gerns 1995, 170) (fig. 3). The aesthetics of marble along with the technical developments of attachment systems enabled builders to "enhance the clean, sleek line of contemporary structures" (Cantor and Juda 1988, 3). With standardization, thin stone panels became one of the prefabricated parts of curtain wall construction systems. "New skills, new equipment, and accelerated schedules dramatically changed how labor was used. Completion quickened, standardization maximized interchangeability, and quality increased at lower costs" (Lewis 1995, 16). Technology of stone cutting continued to evolve from the 1960s through the 1980s, with the use of thin

marble panels increasing by 800% in the 1980s following the advent of new and evolving attachment systems (Brock 2005, 101).

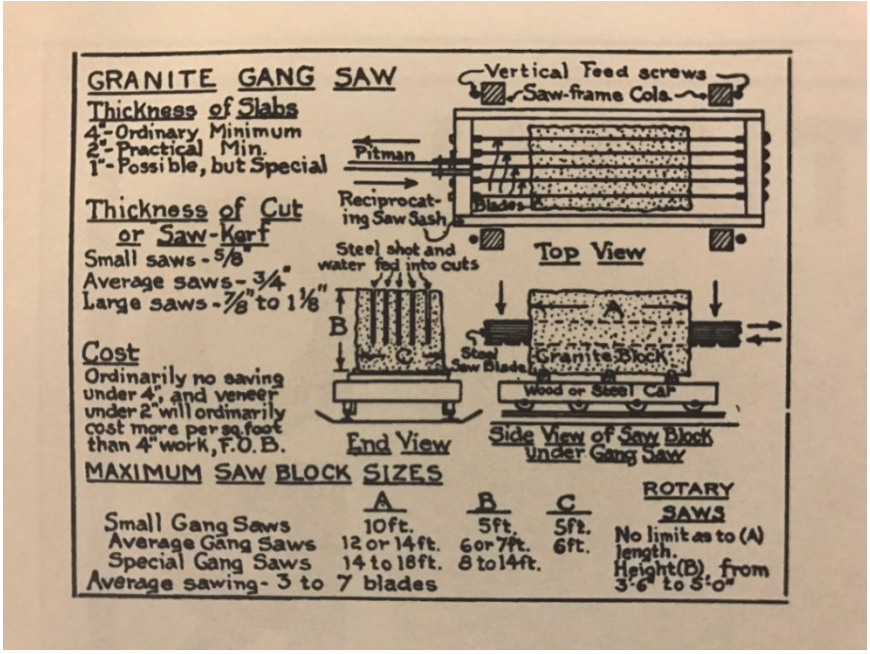


Figure 3: The process of cutting thin granite panels, as described by an advertisement made by the National Building Granite Quarry Association (Source: Scheffler and Gerns 1995, 170).

The modern concept of the curtain wall came from the aesthetics and materiality of the International Style. Its implication of the

> universality of approach which generally favor lightweight technique, synthetic modern materials and standard modular parts so as to facilitate fabrication and erection. It tended as a general rule towards the hypothetical flexibility of the free plan, and to this end it preferred skeleton frame construction to masonry (Frampton 1980, 248).

The International Style came into the public realm through an exhibition by Philip Johnson and H.R. Hitchcock, at the Museum of Modern Art in New York City in 1931. Their concept of a modern wall was defined as "the skin or veneer of a structure should be

detailed to express a thin, continuous surface" (Lewis 1995, 16), using modern materials of "painted stucco or tile…aluminum, thin slabs of marble or granite, and glass, opaque and transparent" (Hitchcock and Johnson 1995, 14). Thin marble panels fit within this new style, in the material's aesthetic and its reducing economic impact on a project. Following the International Style, Modernist and Brutalist aesthetics increased the use of stone and concrete for exterior cladding (Ripple 2012, 16). The many phases of the Modern Movement "expressed the desire for clean, sleek façades devoid of any classical or traditional ornamentation, which allowed stone, a conventional building material, to reemerge for a new, modern purpose" (Ripple 2012, 20).

As a way to make their materials "modern," marble companies advertised for the use of thin marble panels as a viable and inexpensive construction material. The Vermont Marble Company Archives – held by the University of Pennsylvania Architectural Archives – contains numerous full-page colored advertisements from national publications, as well as small booklets and pamphlets produced by the company. With titles, such as "This is the Paradox," "Out of the Past," "Marble Goes Modern" and "Marble is a Unique Material," as well as a *New York Times* article titled "Marble Regaining Lost Grandeur with Variety of Forms," the Vermont Marble Company capitalized on the long held aesthetics and rising economic availability of this ancient building material.

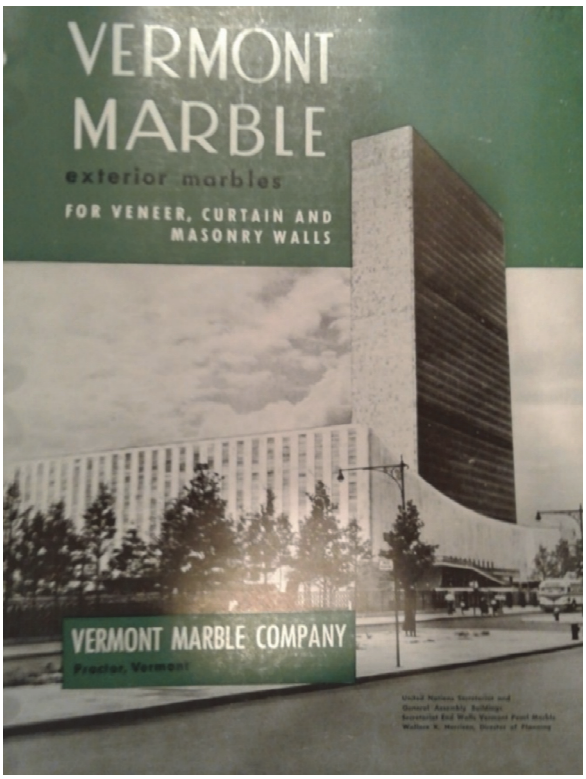
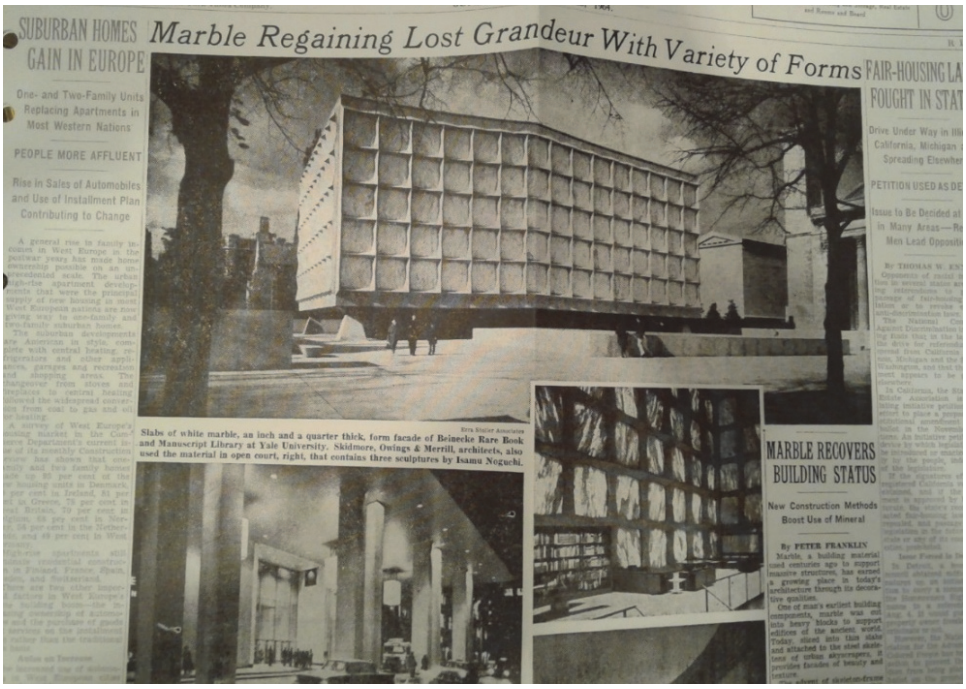


Figure 4: The United Nations Secretariat Building in New York City. One façade is clad in thin veneer panels of Vermont marble. (Source: Vermont Marble Company Archives, University of Pennsylvania, n.d.)

The publications included images of high-profile buildings that were clad with thin marble panels – highlighting the United Nations Secretariat and General Assembly Buildings in New York City (Wallace K. Harrison, 1952), the Beinecke Rare Book and Manuscript Library at Yale University (Skidmore, Owings & Merril, 1960), and the Huntington Hartford Gallery of Modern Art in New York City (Edward Durell Stone, 1964) (fig. 4, 5). Peter Franklin (1964, R1) wrote:

> one of man's earliest building components, marble was cut into heavy blocks to support edifices of the ancient world. Today, sliced into thin slabs and attached to the steel skeletons of urban skyscrapers, it provides façades of beauty and texture.

The Vermont Marble Company was able to capitalize on the new technology of cutting thin stone panels and hanging methods, many of which were patented by the company.[3] Such innovations allowed the use of marble as a thin stone veneer in the 1960s to 1980s to skyrocket.



SUBURBAN HOMES GAIN IN EUROPE

One- and Two-Family Units Replacing Apartments in Most Western Nations

PEOPLE MORE AFFLUENT

Rise in Sales of Automobiles and Use of Installment Plan Contributing to Change

Marble Regaining Lost Grandeur With Variety of Forms

Slabs of white marble, an inch and a quarter thick, form facade of Beinecke Rare Book and Manuscript Library at Yale University. Skidmore, Owings & Merrill, architects, also used the material in open court, right, that contains three sculptures by Isamu Noguchi.

MARBLE RECOVERS BUILDING STATUS

New Construction Methods Boost Use of Mineral

By PETER FRANKLIN

FAIR-HOUSING LA FOUGHT IN STAT

Figure 5: New York Times article on the modern use of thin stone panels by the Vermont Marble Company for the Beinecke Library at Yale University (Source: Vermont Marble Company Archives, University of Pennsylvania, 1960).

[3] As an effort to promote the use of marble in modern construction, the Vermont Marble Company and other larger companies within the natural stone industries developed their own forms of hanging and attachment systems before the methods were standardized. The VMC both published information of application systems – included in pamphlets such as "Marble for Exteriors" and "Marble-Faced Precast Building Panels," as well as patenting certain methods.

1.3 Contemporary Preservation Methods

It has been noted that when marble panels on exterior façades begin to bow, the typical treatment method is complete replacement. This is primarily due to safety concerns from the possibility of panels falling, and the preference for uniformity of appearance through replacement. This is a lengthy and expensive process, such as the replacement of the 43,000 marble panels on the Amoco Building at the cost of roughly $60 million (Logan et. al 1993; Cohen and Monteiro 1991, 114). Complete replacement has also been seen in New Orleans cemeteries when the large single-panel marble tomb enclosure tablets fail due to deformation.

Although safety issues were addressed by the removal and replacement of the thin marble panels, they were typically replaced by more stable materials such as granite or metal panels. This often compromises the aesthetic design intent of the marble paneling on the exterior of a building. In other cases, the bowed marble has been replaced with thicker panels which requires costly detail modifications. In the case of the tomb enclosures in New Orleans cemeteries, complete replacement compromises the historical significance of the original tablet inscriptions and sculptural relief.

Because many examples of thin marble panel clad buildings were constructed in the Post War period, the structures "built for corporate America, were not meant to last forever, and are now in need of major upgrades for computerized and electronic office technologies" (Rappaport 1998, 60). The early concerns of contractors about the lack of material property awareness and the use of improper or inferior materials proved true in

many cases, with marble veneer panels acting inconsistently across a single building façade (Wood 1988, 141). In an essay titled "Preserving Modern Architecture in the US," Nina Rappaport (1998, 63) lists the issues and questions pertaining to the preservation of modern architecture as: (1) the increased obsolescence of the building types, (2) how to conserve the modernist building materials, which were not always made with the goal to last forever, (3) if the building should be preserved as a whole, not as a collection of parts, (4) the relationship between the design of interiors and exteriors, and (5) the preservation of designed plazas. As many of the buildings constructed during the Modernist period are now, or will soon, reach 50 years after construction – making them eligible for National Register of Historic Places' status – these questions will become more relevant. Criteria should be developed to determine if failing modern building materials are worth conserving, or if replacement truly is the best option.

1.3.1 Replacement over Conservation: Case Studies

The current preservation strategy of replacement over conservation can be seen in numerous case studies. As one of the most prominent cases in the United States, the Amoco Building – designed by Edward Durell Stone – in Chicago was re-clad only 20 years after construction, at a huge cost. The Carrara Alpha Gray marble panels that were 1 ¼ inches thick, showed outward displacement up to 28.6 millimeters – which was discovered during building inspections in 1985, 15 years after construction (Loughran 2007, 12-13) (fig. 6). Because the majority of the deformation occurred on the south and east elevations, environmental hysteresis is believed to be the main cause of the bowing. In order to retain

the white marble aesthetic, white granite, white aluminum and ceramic glass panels were considered for the replacement material; Mount Airy Granite was eventually chosen based on performance, cost and availability.[4]

Figure 6: Concave and convex bowing of the Carrara marble panels on the Amoco Building in Chicago from 1987 (Source: Logan 2004, 457).

[4] Thin granite panels have been frequently chosen as the replacement material for bowed thin marble panels because of these characteristics. The aesthetics are some-what similar to that of marble, and unlike other replacement materials it continues the use of masonry. Granite is preferable as a replacement material because of its low possibility for hysteresis, low porosity and high flexural strength.

The Lincoln Bank in Rochester, New York, designed by architect John Graham & Co., was constructed at the same time as the Amoco Building, and was also clad in a white Carrara marble. It was only ten years after construction that the one-inch-thick panels displayed bowing. The building was re-clad with 13,000 lightweight aluminum panels in the early 1980s (Loughran 2007, 17).

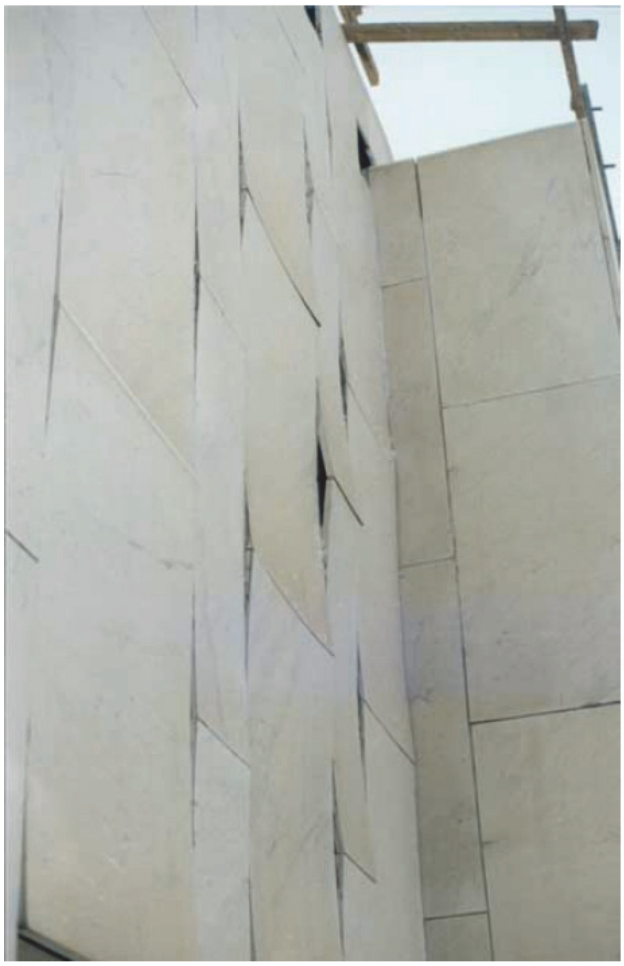


Figure 7: Bowed marble panels on the façade of Finlandia Hall from 1998 (Source: Grelk et. al 2007, 106).

Alvar Aalto's Finlandia Hall in Helsinki is another well-known example of the extent of deformation caused by environmental hysteresis (fig. 7). Constructed between

1967 to 1971, the building was also clad in 1 ¼ inch thick Carrara marble. Cracking was noticed in the exterior veneer panels, and after a panel fell in 1991, safety nets were installed (Loughran 2007, 18). In 1999, replacement of the bowed marble panels with a slightly thicker Carrara marble panel veneer at a cost of 3 million euros. By 2001, bowing of the replacement panels was noticeable again (Loughran 2007, 19).

The La Grande Arche de la Défense in Paris, France, designed by Johann Otto von Spreckelsen, exhibited bowing 15 years after construction in 1989. The panels bowed 20-30 millimeters out of the original plane; the complete replacement was set to finish at the end of 2016 with a budget of 192 million euros (Barriquand-Treuille n.d.; Grelk et. al 2007, 108). At Richmond City Hall, Virginia, designed by architect Elijah E. Myers, the 23,000 marble panels were replaced with a metal panel system just under 30 years after construction (Grelk et. al 2007, 109).

The National Air and Space Museum in Washington, DC, designed by Gyo Obata, is currently involved in a six-year, $365 million renovation that includes replacing the bowed Tennessee pink marble veneer panels with replacement panels that are 1.5 inches thicker (Goldchain 2015). The current panels, which are 5 feet by 2.5 feet by 1 ¼ inch, have bowed and cracked to the point that they are considered a safety concern. The Tennessee pink marble panels on I.M. Pei's National Gallery East Wing also began to bow, but it was determined that this was more due to how the panels were secured to the interior frame. The bowed panels – which are three inches thick – still had a flexural strength that met the current ASTM standard and were rehung (Flanagan 2015).

The marble enclosure tablets of New Orleans' above-ground cemeteries have long been known for their deformation due to the perfect combination of environment and design (Winkler 1975; Matero 1981; Hannibal 2015). The warping of horizontal tablets was first written about in the 19th century by A.A. Julien for the U.S. Census Office.[5] Typically, both horizontal and vertical marble tablets found in cemeteries have bowed mainly due to their relative thinness compared to their length and width (Hannibal 2015, 3). In the above-ground cemeteries of New Orleans, the marble closure tablets typically bow because they are constrained from natural movement. Originally thought to be rock creep from internal stresses, it is now thought to be caused by the combination of daily temperature cycles and the high humidity in New Orleans (Winkler 1975, 43). The bowing of the marble closure tablets is a widely known, and photographed, phenomena (fig. 8). These photographs help to show deformation over time, and when the marble closure tablets have been replaced. Matero et. al established guidelines for the preservation and restoration of the marble closure tablets, calling for the use of "white, preferably Carrara marble, of greater thickness (1 ½ if possible)," set on lead or polyethylene-foam shims to allow for expansion (Matero et. al 2002, 59). While the replacement with a thicker marble

[5] A.A. Julien commented on the deformation of building stone through exposure to the sun, writing: "subjection to wide differences of temperature on different faces, e.g. those produced by the burning heat of our summer sun on the western faces of buildings, renders the stone liable to crack from unequal contraction and expansion…the former is abundantly illustrated in the marked decay and splitting observed on the western faces of the tombstones in Trinity church-yard…" (Julien 1884, 380). Although the use of THIN stone panels was relatively limited to horizontal and vertical tablets in cemeteries in this time-period, the bowing phenomenon was recognizable.

tablet will help to discourage warping, it is possible that any historical information or any carved features on the original stone would be lost.

Figure 8: Bowed marble closure tablets at St. Louis I Cemetery in New Orleans (Source: L. Midelfort 2017).

1.4 Deformation Mechanisms

The bowing of thin marble panels had been previously seen in cemeteries in Europe and North American, but the correlation was never made between this phenomenon and the bowing of exterior façade panels (Hannibal 2015, 3). There have been numerous cases of

upright gravestones and horizontal tablets that have warped over centuries; these can be seen in cemeteries in New Orleans, LA, Philadelphia, PA, and Bologna, Italy. Typically, this occurs when a thin marble panel is constrained from natural expansion and contraction. The belief was that the warping was caused by a number of factors including thermal stressing, freeze-thaw damage, and creep.[6] By studying the damaged panels from the Amoco Building, Logan et. al (1993) made the hypothesis that the panels were bowing due to two factors: "

> (1) thermal cycling due to exposure to sunlight [that] produced a loss of strength in the marble and (2) this in turn allowed the release of residual strain resulting in elongation of the panel that lead to bowing, and further loss of strength along the hinge line of the bow (Logan et. al 1993, 1531).

By this time, hypotheses on the cause of bowing were beginning to evolve because of the many cases that were located in areas with limited freeze-thaw cycles.

1.4.1 Evolution of Deformation Mechanism Hypotheses

In the earliest literature review on the durability of marble cladding, Cohen and Monteiro (1991) point out that while American standards under the American Society for Testing and Materials (ASTM) for the physical properties of marble are determined for

> compressive strength, flexural strength, shear strength, modulus of elasticity, density, absorption (48-hour soak), thermal conductivity k, water vapor

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[6] This hypothesis was formulated by E.M. Winkler (1975). Fluctuations in temperature lead to the thermal expansion and contraction of the calcite grains, which expand parallel and contract perpendicularly to the c-axis (Winkler 1975, 44). Winkler also described the phenomenon of bowing as plastic deformation; defined as "a thin slab of crystalline marble supported on both ends of the slab gradually tends to bend through the unsupported midsection under the own load of the slab," that has been accelerated by the high relative humidity of the atmosphere (Winkler 1975, 57). An image of above-ground vaults in a cemetery in New Orleans accompanies the text, showing bowed marble closure tablets.

> permeability, coefficient of thermal expansion, and creep deflection (after 24 hours) (Cohen and Monteiro 1999, 116)

there are no tests for microstructural differences or long-term creep. Based on these tests, the earliest hypotheses for the cause of marble panel deformation were based on freeze-thaw cycles and how the panels were anchored to the interior structural system.

Various marble companies, including the Vermont Marble Company and the Georgia Marble Company, offered advice on the proper placement and application of structural anchors to reduce the likelihood of bowing (Cohen and Monteiro 1999, 118). Cohen and Monteiro (1999) conclude with the statement that the study of the cause of permanent bowing needs to be a priority because

> there is a controversy among experts about the causes of the residual strains (i.e., permanent bowing) found in the marble, the effects of the restraints provided by the anchorages, and their relation to the crystal size and microstructure of the various marbles that presently qualify for use as exterior cladding (Cohen and Monteiro 1999, 122-123)

and the hypothesis that the permanent bowing of marble panels is an engineering issue.

Early hypotheses also looked at the influence of rising pollution levels as the cause of material degradation in industrial centers. It was believed that the cyclic process of the dissolution and precipitation of carbon dioxide, sulfur dioxide and nitric acid in marble building stone lead to greater porosity percentages and cracking (Cohen and Monteiro 1999, 119). Later testing has shown that the speed of deterioration from the exterior to the interior face of the stone from acidic conditions is too slow to cause deformation at the scale that has been observed (Grelk et. al 2007, 119).

Figure 9 and Figure 10: The magnitude of bowing that can be possible. On the left is the Zagrepcanka business tower in Zagreb, Croatia. (Photo by Jan Anders Brundin) and Finlandia Hall in Helsinki on the right (Photo by Elmar Tcheg). (Source: Grelk et. al 2007, 108).

In the early 2000s, a European program titled the Testing and Assessment of Marble (TEAM) began research into the actual causes of bowing in thin marble panels. The researchers reached the conclusion that the bowing of thin marble panels was caused by the addition of moisture along with daily heat cycling that causes the disaggregation of calcite grains in marble; otherwise known as environmental hysteresis, which was first suggested as a hypothesis in 1999 by B. Erlin (TEAM 2001, 22). TEAM's testing program

involved nine Work Projects: (1) a literature study and survey of stone projects, (2) detailed case studies, (3) long-term monitoring, (4) sampling and influencing parameters, (5) full scale laboratory testing, including quarry and processing variables, (6) development of the bow-test and wet-expansion test, (7) field exposure and possibilities to prevent the bowing or decrease the speed of aging, (8) guidelines for production and product control, and (9) dissemination (Schouenborg et. al 2007). Of the 200 buildings that were identified during the survey of stone projects, the six chosen as case studies represented different marble types and climates, all of which were in Europe (Schouenborg et. al 2007, 125) (fig. 9, 10).

1.4.2 Environmental Hysteresis

Environmental, or thermal, hysteresis can be defined as the disaggregation of calcite grains through daily cycles of heat and moisture that causes sugaring and eventual warping. The process has been heavily studied since the catastrophic failures of thin marble panels on Post War buildings that occurred in the 1970s. It is a process that only occurs under a certain set of environmental and building conditions, but has been seen worldwide in a variety of situations. The extent of the deformation depends on the type of marble, its microstructure, how the panels were attached to the building's structural system, and the climatic conditions of the site (Schouenborg et. al 2007, 135). Although the cause of the deformation has been studied, the warping of exterior marble veneer panels still occurs, as is the case of the National Air and Space Museum in Washington, D.C., showing that while the source may be known, thin marble panels are still being designed and used.

Following the publication of A.A. Julien's "The Durability of Building Stones in New York City and Vicinity" in 1884, authors – such as George W. Bain and D.W. Kessler – developed varying hypotheses about the relationship between the microstructure of marble and its deformation characteristics (Kessler 1919; Bain 1941; Hannibal 2015). An early hypothesis that the cause of the deformation of thin marble panels was environmental hysteresis was introduced by George W. Bain in a publication for the Vermont Marble Company titled the "Warping of Marble," stating that

> warping is also due to unequal moisture absorption such as occurs when one side of a slab is kept dry while the other becomes wet. This sort of warping is independent of total amount of openings and is dependent upon initial dryness of the stone and difference in relative humidity on the two sides of the slab (Cohen and Monteiro 1991, 122)

which causes the movement of calcite grain boundaries (fig. 11). In the same paper, however, Bain also commented that the cause of warping was through inadequate supports and vibrations in the stone. Logan et. al concluded that the

> thermal cycling and the accompanying anisotropic dimensional changes in the calcite fatigue at the grain boundaries eventually cause some to fail. This reduction in tensile strength allows the residual strain within the grains to be released (Logan et. al 1993, 1537).

Again, part of the conclusion stipulated that poor anchor locations can exacerbate panel deformation but they alone are not the cause of the problem.

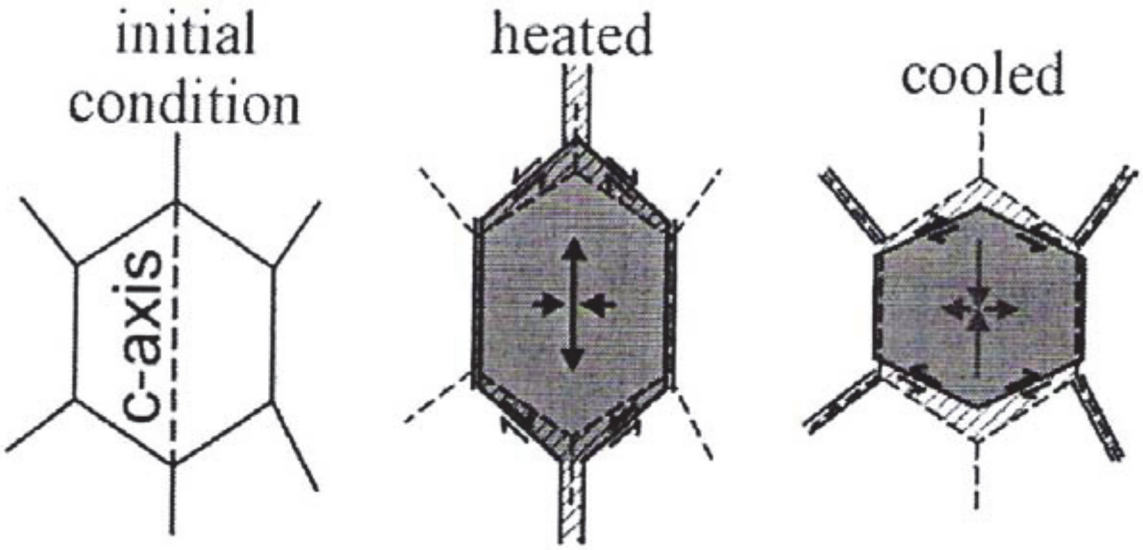

Figure 11: Anisotropic thermal behavior of calcite grains (Source: Grelk et. al 2004, 5).

The TEAM program focused more on the causes of the bowing of thin marble panels as a way to establish guidelines for the selection of exterior veneer stone. From a literature review conducted by TEAM, the conclusion was that the two common factors in all of the case studies included were "a daily temperature variation and a source of moisture" (Grelk et. al 2007, 113). Greater fluctuation in temperature and higher humidity have been linked to a greater magnitude of bowing. Through the TEAM program's literature review and subsequent testing, the program was able to refute many of the previous hypotheses for the cause of bowing (Malaga et. al 2008, 110). Later articles written by TEAM members then linked a daily temperature fluctuation and a moisture source to the disaggregation of calcite grains, which leads to uneven expansion and contraction.

1.4.3 Disaggregation of Calcite Grains

With temperature fluctuations and moisture, calcite grains within marble disaggregate due to anisotropic thermal expansion, which leads to bowing (Akesson et. al 2006, 74). As part of the TEAM program, different marbles that had either a xenoblastic or granoblastic texture – either anhedral grains surrounded by subgrains or even sized crystals with smooth grain boundaries, respectively – were tested to determine the effect of the microstructure of the marble on the extent of the bowing. The authors concluded that there was a "good correlation between the number of adjacent grains and the degree of bowing. The samples with fewest adjacent grains showed the greatest degree of bowing" (Akesson et. al 2006, 79) or granoblastic marbles displayed a greater vulnerability to warping than xenoblastic marbles in the same environmental conditions.

Later articles from the TEAM program refuted this hypothesis, mainly because granular decohesion was not always found to be the cause of bowing in all types of marble tested (Malaga et. al 2008, 111). In many cases, bowing is caused by the build-up of internal stress brought on by the recrystallization at grain boundaries caused by temperature variations and added moisture. It can also be dependent on the "individual grain to grain orientation, i.e. the misorientation, [which] may produce internal stresses leading to microcracking;" this could potentially be caused by microcracks formed during the quarrying process (Siegesmund 2008, 488). Siegesmund et. al (2008) summarized their findings on an investigation on three buildings which exhibited marble façade panels

bowing as a degradation process that is controlled by interactions within the marble fabric, as well as the residual strain brought on by thermal cycling.

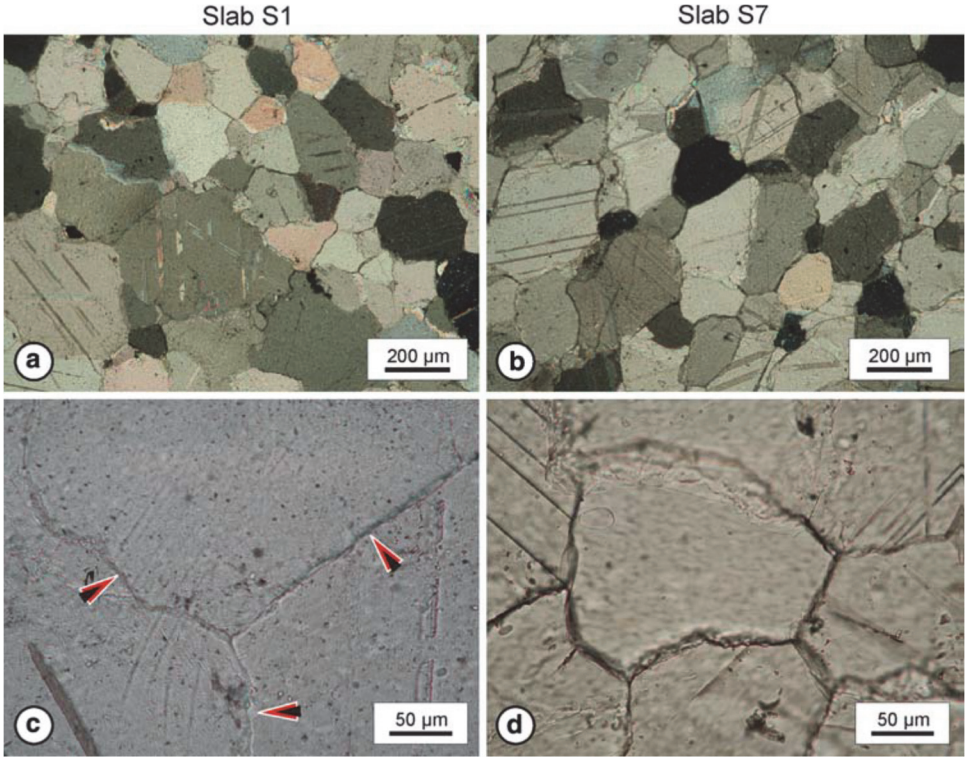

Figure 12: Thin section images of slightly bowed (Slab S1) and strongly bowed (Slab S7) marble slabs. The bottom two photographs show the degree of disaggregation of calcite grains after bowing (Source: Siegesmund et. al 2008, 485).

Subsequent authors tested the effects of shape fabric and crystal texture on "stored elastic strain energy density and microstructural stresses, which influence marble degradation" based on the previously presented evidence (Shushakova et. al 2011, 1589). A team from the University of Parma's Department of Civil-Environment Engineering and Architecture developed a micromechanical model to predict thermal fatigue and the suspected bowing of certain marbles dependent on anisotropic thermal expansion (Spagnoli et. al 2011, 2557). Like Shushakova et. al, their subsequent research was

dependent on the earlier studies of pubic building marble façades that exhibited bowing. They again found a correlation between the material microstructure and the magnitude of the bowing, which relates to the measure of internal stress developed within the material due to daily temperature fluctuations (Ferrero et. al 2014, 51).

Following the TEAM program, a European standard was created to test the resistance of marble to thermal cycling, adopted as EN 16306, which was aimed at "replicating the worst-case temperature increase and moisture gradient observed" (Bellopede et. al 2016, 2). The testing standard assesses the magnitude of bowing, an analysis of adjacent grains, and the flexural strength of the marble panels. A later study of the standard conducted by Bellopede et. al (2016) evaluated the testing program's usefulness; concluding that the standard's testing of the potential bowing magnitude and flexural strength correlate to the marble's long-term performance (Bellopede et. al 2016, 7). Bellopede et. al (2016) also showed a correlation between the flexural strength and water absorption of the marbles tested, suggesting the importance of the testing program outlined by EN 16306 in determining the effects of thermal and moisture cycles on the magnitude of bowing.

1.5 Justification

The process of inducing the bowing of thin marble panels was explored by TEAM, whose main objectives were "to understand and explain the expansion, bowing, and strength loss mechanisms governing the decay of marble and limestone clad façades, and to draft new European standards to prevent the use of marble and limestone poorly suited to outdoor

cladding" (Malaga et. al 2008, 97). This was followed by a master's thesis by Sandy Cross in 2005, at the University of Pennsylvania, who replicated TEAM's process and explored possible mechanical treatments. Later authors expanded on TEAM's conclusions, looking more closely into the disaggregation of calcite grains through the process of environmental hysteresis as the main cause of marble sugaring, or granular decohesion, and eventual bowing. The thought that the study of calcite grain boundaries for the selection of marble building stone goes back to the work of George W. Bain in the 1940s, who studied the warping of marble panels, as well as using early petrographic analysis to determine the distance between calcite grains.

While the mechanisms of deformation for the bowing of marble panels are known and have been well studied, more work now needs to focus on treatment methods that will improve the compromised flexural strength, and that will function as part of a veneer wall system. Although there are numerous methods for the mechanical treatment of concrete and masonry slabs, these treatment methods need to be evolved to meet the above conditions. This thesis will build upon the previous research on deformation, as well as adapting mechanical treatments for other masonry features in order to improve upon the compromised flexural strength of bowed marble panels. The upcoming chapters will delve deeper into the testing methodology outlined by the TEAM program and the 2005 master's thesis, along with recent research into the use of concrete and masonry panel mechanical reinforcement on marble panels.

CHAPTER 2: METHODOLOGY

2.1 Use of Carrara Marble

Carrara marble is one of, if not the most widely used marble for thin panel veneer; it is also marble that displays inconsistent mechanical behavior due to its variable microstructure (Malaga et. al 2008; Grelk et. al 2007; Loughran 2007; Hannibal 2015). According to the TEAM testing program, Carrara marble proved to be a poor choice when used as a thin panel veneer (Malaga et. al 2008, 100). The TEAM program also concluded that almost all calcitic marbles – including Carrara, Vermont and Portuguese – exhibited bowing in documented cases, while only few types of dolomitic marbles appeared (TEAM 2001, 6). Bowed Carrara marble has been seen in the high-profile cases of the Amoco Building in Chicago and Finlandia Hall in Helsinki. New Orleans cemeteries had originally promoted the use of Carrara marble for memorials, a location where the phenomenon of warped tomb enclosure tablets is frequent (Hannibal 2015, 4). It was for these reasons that Carrara marble was chosen for testing to evaluate the performance of mechanical treatments that are subjected to bowing potential tests.

It has been noted that the most important parameters that lead to potential bowing are the following: grain size, grain interlocking, and grain boundaries (TEAM 2001, 11; Malaga et. al 2008, 111; Shushakova et. al 2011, 1588; Akesson et. al 2005, 74). Cohen and Monteiro (1991) suggested that there is a correlation between a high volumetric change and marble, with a microstructure of loosely packed, small spherical grains. Grain interlocking and grain boundaries have also been linked to changes in porosity and flexural

strength by numerous authors (Oliveira et. al 1994; Zezza 1993; Howarth 1986; Royer-Carfagni Oct. 1999). In the testing carried out by Oliveira et. al (1994), it was shown that Carrara marble with a loose, rounded grain texture displays the greatest potential to have a high magnitude of bowing under certain conditions. George W. Bain first wrote about this phenomenon in 1940; his investigations into Vermont marble showed that marbles with straight grain boundaries were more susceptible to degradation compared to marbles with irregular grain boundaries (Bain 1940).

Another factor to consider when selecting a marble type is its microstructure, or texture. Texture is typically determined by grain boundaries;

> homoblastic [now referred to as granoblastic] textures are composed of regularly shaped grains with straight or gently curved boundaries, whereas xenoblastic textures are characterized by the close interlocking of irregular crystals closely fitting along their contours (TEAM 2001, 12) (fig. 13).

Later studies by the TEAM program into the influence of microstructure on the magnitude of bowing concluded that there is a correlation between the magnitude of bowing and the number of adjacent grains; the fewest adjacent grains had the greatest magnitude (Aeksson et. al 2005, 79). Royer-Carfagni (Oct. 1999) tested four types of Carrara marble with different textures and found that the samples with a xenoblastic texture were much more resistant to thermal cycling than granoblastic textured samples.

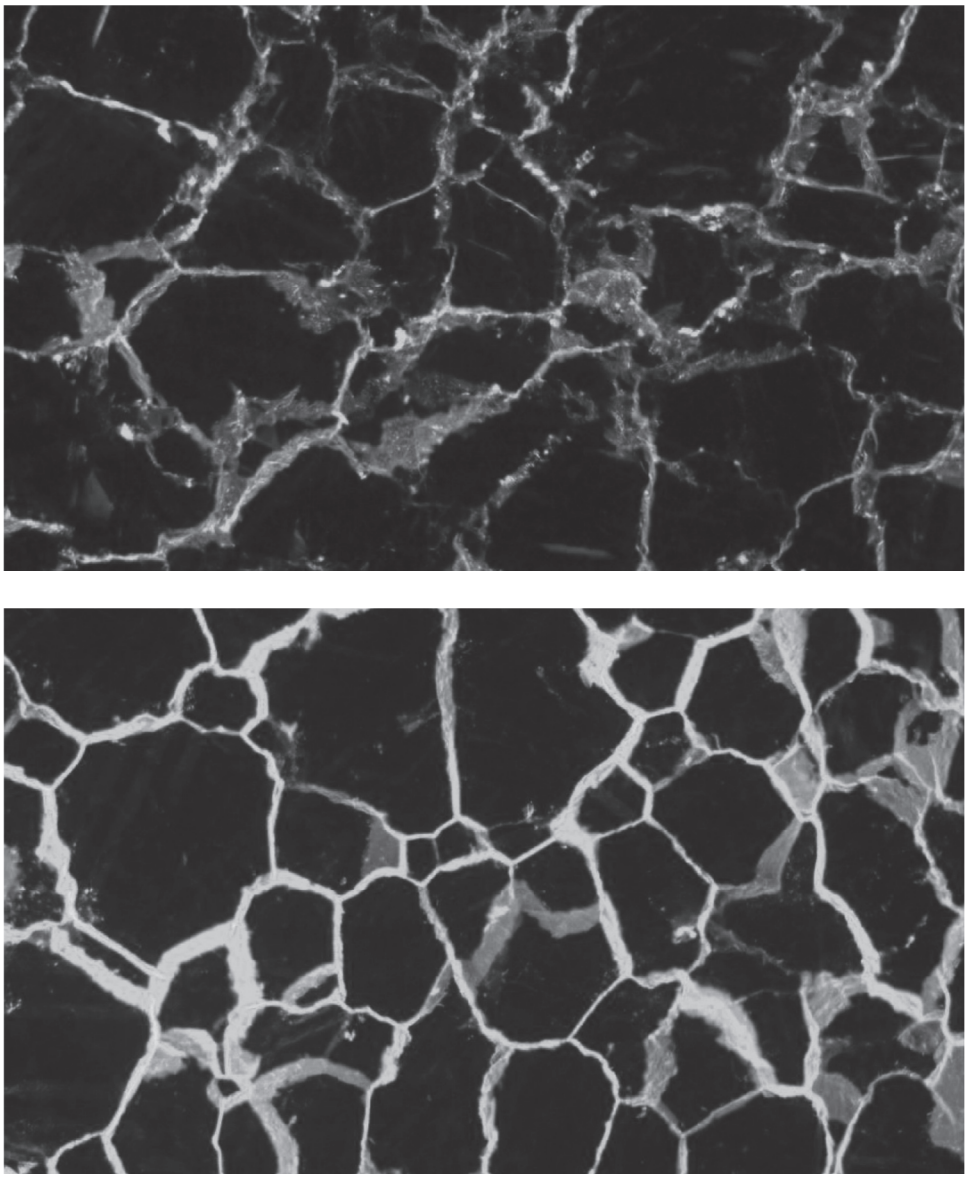

Figure 13: The image on the top shows a marble thin section with a xenoblastic texture, while the image on the bottom shows a marble thin section with a granoblastic texture. The simple structure and smooth grain boundaries are clearly evident in the right-hand image (Source: Malaga et. al 2008, 106).

2.2 Mechanical Reinforcement Systems

Although the phenomena of bowing in thin marble panels is known and its causes have been heavily researched and tested, no mechanical treatments have been proposed to improve the compromised flexural strength of bowed panels – the treatment has exclusively been replacement (Logan et. al 1999, Hannibal 2015, Grelk et. al 2007). Applied mechanical treatments have been used to increase the flexural strength of concrete panels and beams, and as a method to make repairs (Cross 2005; Kaufmann et. al 2007; Brena et. al 2003; Pujadas et. al 2014). The treatments have included: plastic fiber amended mortars, carbon fiber straps and webbing, and carbon fiber reinforced polymer composites. Along with concrete reinforcements, there is also a history of testing mechanical treatments for masonry panels – exclusively stone and mortar systems – in terms of reinforcement in seismic zones. These articles were explored in terms of testing procedures and strapping methods that could be used for bowed marble panels.

2.2.1 Concrete and Masonry Panel Reinforcement

Literature on concrete and masonry panel reinforcement from the past ten years has focused on developing systems to model failure in panels, and to predict how reinforcements will mitigate those damages. Authors have also examined new technologies used to create component and bi-component fibers, along with fabric reinforced cementitious matrix (FRCM) systems. Various combinations of fibers and mortar or epoxy resin systems have been tested for flexural strength in both in-plane and out-of-plane loading to determine failure modes (Papanicolaou et. al 2011). Some testing has shown

that textile reinforced mortars (TRM) are more effective in terms of deformation capacity when compared to fiber reinforced polymers (FRP) (Papanicolaou et. al 2011, 514).

Luccioni and Rougier (2011) looked at the various application locations of carbon fiber reinforced polymers (CFRP) on masonry panels to determine failure locations under compression. Under certain conditions, the location and width of carbon fiber straps can increase the ductility and ultimate strength of masonry panels (Luccioni and Rougier 2011, 1787) (fig. 14). They concluded that the use of diagonal CFRP bands helps to improve the ductility and failure mode of masonry panels (Luccioni and Rougier 2011, 1787). The use of basalt fiber textiles has grown as well, as the technology behind the fibers has increased. Basalt fibers are composed of extremely fine fibers of basalt; a stone which is typically composed of plagioclase, pyroxene and olivine minerals (Singha 2012, 19). The quarried basalt is "crushed, washed and loaded into a bin attached to feeders that transfer the material into melting baths in gas-heated furnaces" and is then put through a horizontal shaft fiber spinning machine (Singha 2012, 20). Basalt fibers have a larger strain to failure than carbon fibers, and are non-combustible, have high chemical stability and are non-toxic (Marcari et. al 2017, 131). The testing program outlined in Marcari et. al (2017) of basalt textile reinforced mortar composites (BTRM) showed an increase in shear strength and ductility, along with the method being a non-invasive system that is suitable for historic structures while using a mortar backing.

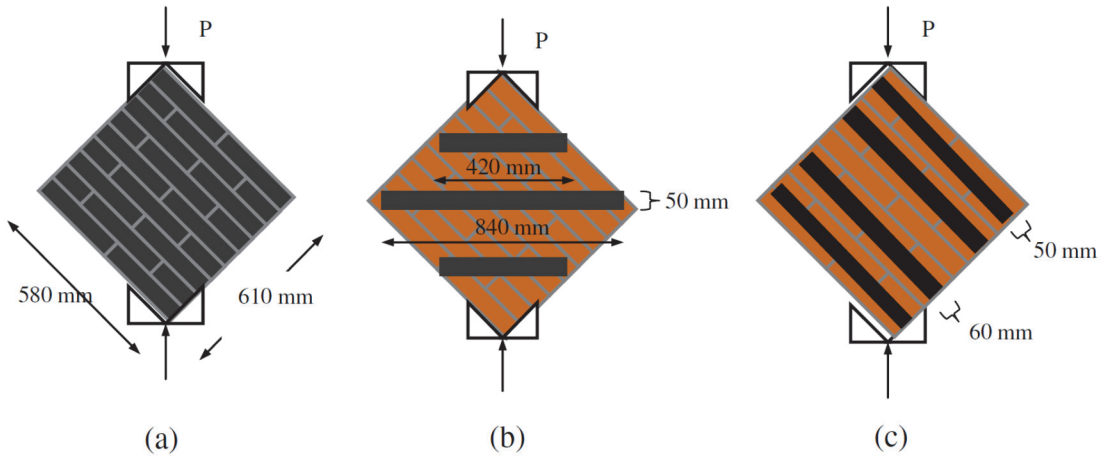

Figure 14: Methods of masonry panel reinforcement (Source: Luccioni and Rougier 2011, 1777).

The earlies studies on CFRP treatments focused on its use as a way to increase the flexural strength of a building material (Brena et. al 2003; Alagusundaramoorthy et. al 2003). It has also been documented that CFRP systems do not always bond well to with masonry, and can be incompatible with the masonry substrate (Triantafillou and Papanicolaou 2005, 100).[7] Triantafillou and Papanicolaou (2005) concluded that textile-reinforced mortars behaved better in compressive strength and deformability when compared to CFRP systems.

[7] The test samples from Cross (2005) remained in storage at the Conservation Lab at the University of Pennsylvania. In the 12 years since the original testing took place, the marble panels that were treated with a CFRP epoxy system showed evidence of poor aging. The epoxy has discolored, and the carbon fiber straps were easily removed from the substrate.

2.2.2 Limitations of Creating a Vapor Barrier

While the most prevalent form of mechanical treatment for concrete repairs is a fiber reinforced polymer (FRP) system, because the epoxy used in these systems forms a vapor barrier it is not a suitable repair method for bowed marble panels. This is because in cavity wall systems, water vapor needs to be able to move freely through the thin veneer panels to prevent moisture build-up. The use of CFRP strips would limit the surface area not covered with the epoxy system, and blocking the moisture transport in certain areas could exacerbate the deterioration in other portions of the marble panels.

Carozzi and Poggi (2015) examined the differences between FRP and fiber reinforced cementitious matrix (FRCM) systems. While effective, FRP systems have the drawbacks of "poor behavior at high temperatures, relatively high costs of epoxy resins, lack of vapor permeability, incompatibility of resins and substrate materials, [and] no reversibility of installation" (Carozzi and Poggi 2015, 215). Due to its vapor permeability and greater compatibility with masonry substrates, FRCM systems are now used increasingly for reinforcements in historic structures. Mortar-based reinforcements also address requirements for the preservation of cultural heritage:

> (1) respect of authenticity in terms of materials and structural behavior, (2) principle of minimum intervention, (3) reversibility, intended as substitutability and removability, (4) compatibility with original substrates and decorative settings, (5) durability (De Santis et. al 2015, 401).

Carozzi and Poggi (2015) tested polyparaphenylene benzobisoxazole (PBO), glass, carbon and bi-component fiber grids embedded in specified mortar formulations for their tensile

stresses and strains, while De Santis et. al (2015) tested glass and aramid bidirectional fabric, and unidirectional galvanized high tensile strength steel mesh in a variety of mortar formulations to determine the system's tensile strength. Both found that the tensile strength of the system was linked to the properties of the mesh used (Carozzi and Poggi 2015; De Santis et. al 2015).

2.2.3 Proposed Mechanical Treatment

This thesis tested the effectiveness of a fiber reinforced cementitious matrix (FRCM) system in reducing the bowing potential and increasing the flexural strength of Carrara marble. A FRCM system was chosen because of suitability with the masonry substrate, the high tensile strength of fiber fabric, and the vapor permeability of the system. The products used to create a FRCM system were chosen based on material properties, prices and availability, and thinness of installation.

The carbon fiber mesh types available on U.S. Composites were examined to choose the mesh or fabric that fit the parameters needed, including a high strength and open weave (fig. 15). The chosen carbon fiber fabric is 9.5 oz by 50 inches, giving the weight of the fabric. It has a tow size of 12,000, meaning that there are 12,000 filaments of carbon fiber per each larger thread. It has a thread count of 5 picks by 5 picks, or 5 carbon fibers per every 10 mm. The chosen carbon fiber fabric also has an open weave that allows for easy interaction with the cementitious adhesive matrix. The open weave allows the lower layer of adhesive to form keys through the fabric in order to bond with the upper layer of adhesive. As a heavy-duty carbon fiber fabric, it has a 50 to 70 Msi modulus, which

is a “mathematical value that describes the stiffness of a material by measuring its deflection or change in length under loading” (Staff 2014). The carbon fiber fabrics that had a higher Msi modulus did not have an open weave, making them incompatible with this system of reinforcement.

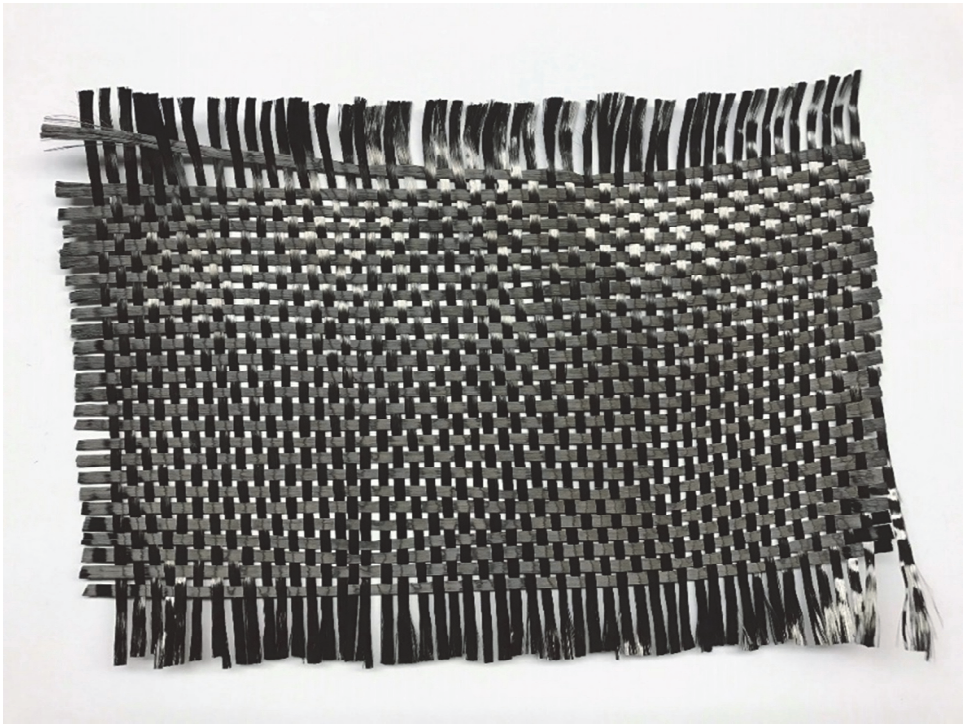

Figure 15: Sample of the carbon fiber fabric used (Source: D. Pape 2017).

The accessibility of carbon fiber products was the primary reason that carbon fiber was chosen over another reinforced fabric. Carbon fiber fabrics typically have a tensile strength that is mid-range when compared to materials such as glass or PBO fibers (Carozzi and Poggi 2015). In tensile strength tests of carbon fiber fabric reinforced cementitious matrices, Carozzi and Poggi (2015) noticed that there was slippage between the matrix and

dry carbon fibers, which is why in the tests for this thesis the carbon fiber fabric was fully saturated with water before it is added to the cementitious matrix. In order to circumvent this circumstance, sample panels were made to test various application methods before the mechanical treatments were applied to the final test panels. The carbon fiber mesh was applied three ways for the sample panels: (1) dry, (2) fully saturated with deionized water, and (3) fully saturated in the adhesive system. The third application method was tested because in FRP systems, the carbon fiber fabric is impregnated in the epoxy prior to application.

A proprietary cementitious adhesive, Rapidry DM 50-75™, part of the Dryvit™ system, was selected as a fast setting, polymer-modified cementitious adhesive (fig. 16). This product was chosen because it does not form a vapor barrier when it cures, and has a high tensile strength. The product also bonds well to masonry substrates. Rapidry DM 50-75™ has high durability and adhesion properties. It was originally designed to adhere polystyrene insulation to acceptable substrates, as well as embedding reinforcing mesh (Dryvit™ Systems, Inc. n.d.). Rapidry DM 50-75™ has a tensile bonding strength of 104 kPa, and has a water vapor transmission of 41 Perms. Because it was designed for embedded reinforcing mesh, the cementitious adhesive should bond well with the carbon fiber fabric. In typical FRP systems, the carbon fiber fabric is first impregnated in the resin or epoxy to allow for better bonding between the two materials. Earlier sample tests to determine the suitability between the carbon fiber fabric and the Rapidry DM 50-75™ showed that when used while the carbon fiber fabric was dry, the two products had a

greater rate of delamination compared to when the carbon fiber fabric was fully saturated with water and immersed in the Rapidry DM 50-75™ mix prior to application.

Figure 16: The testing used Rapidry DM 50-75™ to form a FRCM system to reinforce the bowed marble panels to improve the flexural strength (Source: D. Pape 2017).

The FRCM system was applied in thin layers on the reverse side of the marble panels. First, the Rapidry DM 50-75™ was applied in a thin layer. For each marble panel, 200 grams of the Rapidry DM 50-75™ dry powder was mixed with 50 ml of deionized water until the mortar was smooth with no lumps. The deionized water saturated carbon

fiber fabric was then applied, making sure that keys formed in the openings of the mesh. A top coat of the Rapidry DM 50-75™ was then applied on top, with a wet on wet application. This application method followed the procedure outlined in Papanicolaou et. al (2011); the key formation through the carbon fiber mesh is important to ensure that the two layers of Rapidry DM 50-75™ create a strong bond. The panels were allowed to cure for 48 hours before testing started. Per the specifications, the Rapidry DM 50-75™ adhesive needs 28 days to fully cure, but this was not possible due to time constraints.

2.3 Testing Program

This thesis follows the testing program first outlined by the European TEAM program, which was simplified by a testing program outlined in Cross (2005). A total of nine Carrara marble sample panels were tested: two control panels (C1-2), five panels with the FRCM system (A1-5), and two panels that had previously gone through the bowing potential test for 40 cycles with the FRCM system applied before this testing procedure (CRF 1-2). After the nine samples were allowed a cure time of 48 hours, they were first subjected to the bowing potential test outlined by Nordtest Method: NT BUILD 499. Following the 40 daily cycles to induce bowing, the flexural strength of the panels was tested. This involved the 4-point bending test outlined in ASTM C880.

2.3.1 Vapor Permeability of Proposed Mechanical Treatment

Although the product data sheet for Rapidry DM 50-75™ states that it does not form a vapor barrier, the FRCM system was tested to ensure that the system as a whole – with the carbon fiber fabric and applied on the marble substrate – allowed for acceptable

vapor transmission. The testing program followed the procedure outlined in ASTM E 96-00: Standard Test Methods for Water Vapor Transmission of Materials.[8]

Three disks were cored from a remaining marble panel for testing purposes. The mechanical treatment was applied to the reverse side of the disk, following the same application process as described above. The system was allowed 48 hours to cure before the vapor transmission test commenced, the same cure time as the panels that were tested for bowing potential. The marble system was then dried in a 60 °C oven for 24 hours to remove any remaining moisture from the system. Following this step, an initial weight of the dried system and disposable beaker was recorded to establish the base-line weight. The beaker was then filled with 70 ml of deionized water, and the entire system was weighed again. Liquid paraffin wax was applied around the marble disk to seal the test assembly; the weight of the completed system was recorded and was then placed in a desiccator. The desiccator – theoretically – will draw the water in a vapor form through the marble reinforced system to be expelled. Measurements of the weight of the system were taken over the course of two weeks to determine the loss of water. A rate of water vapor transmission is determined by plotting a straight line of best fit.

[8] The testing procedure for water vapor transmission followed Lab 8: Water Vapor Transmission, which was developed for the course Introduction to Architectural Conservation at the University of Pennsylvania. It is based on ASTM E 96-00, but is more suitable for the time-period of this thesis.

2.3.2 Bowing Potential

Developed in response to major failures in marble veneer panels, the EC-funded TEAM project ran from 2000 to 2005. Their goal to "understand and explain the expansion, bowing, and strength-loss mechanisms governing the decay of marble- and limestone-clad façades" lead to the development of the European standard NT BUILD 499 and EN 16306 to "prevent the use of marble and limestone poorly suited to outdoor cladding" (Malaga et. al 2008, 97). An analysis of over 200 buildings showed the inconsistency of Carrara marble performance; some case studies performed up to the accepted standard, while others bowed both convexly and concavely (Malaga et. al 2008, 98). They verified through testing the following statements:

> (1) Carrara is a poor quality marble, (2) fine-grained marble is suitable for use as cladding, (3) a complex microstructure ensures cladding durability, (4) frost action causes bowing, (5) moisture and temperature variations are crucial to bowing, (6) anisotropic thermal expansion of calcite and dolo[mite] stone causes granular decohesion, and (7) the release of stress locked into rock plays an important role (Malaga et. al 2008, 100).

The TEAM program developed a testing program to measure the bowing potential of marble panels by inducing bowing through daily heat cycles and a moisture source. This testing program evolved into the NT BUILD 499 and the European Standard EN 16306.

The bowing potential test has evolved since its development by the TEAM program, and the testing standard EN 16306 has been assessed for its usefulness as recently as 2016. The standard almost exactly follows the testing procedure developed by the TEAM program, with minor changes about temperature and the number of heat cycles (Bellopede

et. al 2016, 1). By minimizing the temperature range, the testing standard looks to replicate the natural temperature range that exterior façade panels would be in, not the extremes of lab testing. In the assessment of EN 16306, Bellopede et. al (2016) used petrographic analysis to compare the bowing potential and flexural strength results to the sampled marble's change in calcite grain boundaries. Through their testing, one of the results showed that permanent bowing and loss of flexural strength was seen in marbles with grain size less than 0.6 mm; marbles with grain size between 0.5 and 3 mm did not show sensitivity to thermal and moisture cycles (Bellopede et. al 2016, 6). By correlating the results of lab testing to bowed marble panels that were measured in situ, Bellopede et. al (2016) also showed a comparison to the marbles that were considered "dangerous" for their loss of flexural strength in situ and the marbles that reached permanent bowing after 50 thermal and moisture cycles in the lab (Bellopede et. al 2016, 7).

The Nordtest Method: NT BUILD 499 (2002-05) tests for bowing of natural stone panels. It defines bowing as "a term for a slab that has changed from an original flat and plane shape to a curved or dished shaped in a concave or convex direction" (Nordtest Method: NT BUILD 499 2002-05, 1). The bowing is induced through cycles of heat; with one side of the marble slab ranging in temperature from 20 to 80 °C, with one cycle every 24 hours. Heat is added to the system through two heat lamps above the surface of the marble. Moisture is added to the system by resting the marble slabs in a pool of water, resting on glass rods. The marble slabs are subjected to 40 cycles, with daily measurement to determine the magnitude of bowing. The magnitude of bowing is measured with a gauge

placed at a specific point at the center of the top face of the marble slab, with the piece resting on two stable steel bars that the marble rests upon. The magnitude is calculated by dividing the change in height, measured with the gauge, divided by the length between the two bars (fig. 17).

Figure 17: System to measure the bowing of the marble panels. The central gauge measures the amount of displacement from a defined zero point. The length between the two steel bars is used to calculate the magnitude of bowing (Source: D. Pape 2017).

Nine marble panel samples were put through bowing magnitude tests. Two samples were controls (C 1-2), and are untreated samples of Carrara marble. Five samples (A1-5) have mechanical treatments applied to the reverse side of the marble panel – this treatment was described in Section 2.3. Two additional samples (CFP 1-2) had been subjected to 40 cycles of the bowing potential test previously; after which the mechanical treatment was applied to the reverse side. This was done to determine the difference in the loss and

hopeful gain of flexural strength between the control panel, unbowed panel with mechanical treatment and bowed panel with mechanical treatment.

Figure 18: Testing apparatus for the NT BUILD 499 bowing potential test (Source: D. Pape 2017).

After the samples with mechanical treatments had fully cured, they were put through the NT BUILD 499 testing procedure. An apparatus was constructed in the Fabrication Lab at PennDesign, following the dimensions of an apparatus that remained in the University of Pennsylvania's Conservation Lab that was built by Cross (2005) (fig. 18). It consists of a wooden base, and two side columns that support a central rail. The rail can be raised and lowered through a series of bolted connections to control the temperature of the system. The two heat lamps hang from the bottom of the rail, providing heat to the system. On the wooden base, a metal pan that is two inches deep holds glass rods. The

marble samples rest in the pan on the glass rods. The pan is filled with water to add moisture to the system. Over the course of a testing cycle, the water level must be maintained to ensure that at least a quarter of the thickness of the marble slabs are submerged.

Measurements of each sample were taken once a day before the heat lamps are turned on. Once activated, the thermal cycle runs for four hours. After the heat lamps were turned off, the system is allowed to return to the ambient temperature of the room for a minimum of 16 hours before they cycle begins again. One full cycle includes measurement, heating and cooling; the bowing potential tests will run for 40 cycles. Following the 40 cycles, the flexural strength of each sample was tested.

2.3.3 Flexural Strength

The flexural strength of dimension stone, which marble panels fall under, was tested following the procedure outlined in ASTM C880. Testing for flexural strength included quarter-point loading, where the load is parallel to the bedding plane (ASTM C880, 1). The nine test panels that were subjected to 40 thermal and moisture cycles will be tested, as well as three test panels that were not put through the bowing potential test: a control panel (C3), an unbowed sample with mechanical treatment, and a sample that had gone through 40 cycles and was then treated. These additional three panels were included to determine the difference in flexural strength before and after mechanical treatments, and to see the magnitude of change in flexural strength following the bowing potential tests.

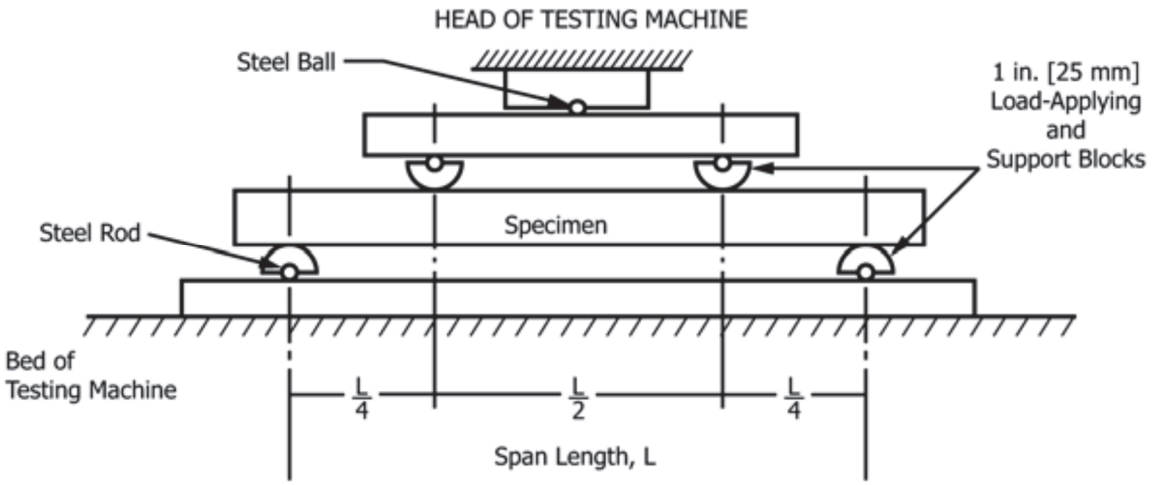

Figure 19: Testing set-up for ASTM C880 to test for flexural strength (Source: ASTM C880).

By subjecting the marble tests panels to bowing potential testing, theoretically the panels should have a loss of flexural strength due to the stressing of calcite grains within the sample. This should be seen between sample C3 – unbowed – and samples C1 and C2, which were put through the bowing potential tests. These samples served as the controls for the flexural strength tests. The outcome of flexural strength tests on samples A1-5 were compared to that of the control to determine whether the mechanical treatment had any effect on the bowing potential of the marble sample panels, as well as determining the difference in flexural strength when comparing the samples with mechanical treatment and without after 40 thermal and moisture cycles. Samples CFP 1-2, which went through the cycling twice – once before and once after mechanical treatment – were compared to sample CFP 3, which was not put through a second 40 cycles. The results of the flexural strength testing on samples CFP 1-3 will be compared to the control sample to determine

whether the mechanical treatment had any effect on the compromised flexural strength of the bowed panels.[9]

Testing the flexural strength of the sample panels is an important step in this thesis to show how the mechanical treatment affects the value compared to the control panel (C3). It is the loss of flexural strength that makes bowed marble panels dangerous when part of an exterior cladding system. Based upon the research done for this thesis, the disaggregation of calcite grains brought on by thermal and moisture cycles leads to this condition. Because the environment that veneer panels exist in cannot be controlled, the application of a mechanical treatment to the reverse of the marble panel – which will not be seen as part of a veneer system – will help to maintain historic fabric on building façades.[10]

2.3.4 Visual Analysis

In addition to mechanical tests, a visual analysis on the marble panels was conducted to assess for visible damage that might occur during testing. Before tested, a

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[9] This data can also be compared to the data collected in Cross (2005). The flexural strength testing done in this thesis included control panels, and panels subjected to 20 and 40 thermal and moisture cycles. Because the same marble panels were used for the testing in this thesis and in Cross, there is a direct correlation in the data points.

[10] The use of mechanical reinforcement applied to the reverse side of bowed marble panels may not be applicable as a complete conservation treatment, but needs to be used in conjunction with new anchoring systems for the marble veneer panels. When the thin marble panels begin to bow, the changing shape puts stress on the anchors tying the panel to the interior structural system – which leads to the failures on the anchors. Because the anchors constrain the expansion and contraction of the marble panels, stress builds up at these locations until failure. After a potential mechanical treatment is applied to bowed thin marble panels, the shape of the panel will no longer correspond to the previous anchor locations. This would lead to a secondary step in the conservation method – creating and locating new anchor locations.

base-line photograph of each panel was taken to compare with later changes. Over the course of the bowing potential tests, photographs of the panels were taken every 20 cycles. The color and surface texture were noted, as well as any visible deformations. This potentially could include any cracks or development of sugaring on the surface of the stone as a way to identifying damage behavior.

2.4 Limitations

Due to time and space constraints, the tests used limited samples and a modified bowing gauge measurement. Enough sample panels were tested to be able to form applicable conclusions and results. Because the bowing potential testing procedure required 40 days of daily cycling, the testing following and preceding this test needed to be straightforward and limited. The Rapidry DM 50-75™ was also not allowed its full 28-day cure time, but only enough time to reach 50% strength before testing occurred. In order to confirm the vapor permeability of Rapidry DM 50-75™, vapor transmission tests were conducted, but occurred at the same time as the bowing potential test because of time constraints. Other physical properties of the marble should be considered, but were not tested due to time constraints. This could include linear strain and water absorption tests, which can also affect the magnitude of bowing (Malaga et. al 2008; Bellopede et. al 2015).

CHAPTER 3: ANALYSIS AND OBSERVATIONS

3.1 Marble Characteristics

The Carrara marble used for the testing program outlined in the thesis is the same marble used in Cross (2005), and has remained in storage at the Architectural Conservation Laboratory at the University of Pennsylvania since 2005. The following characterization includes elements that were done by Cross, as well as an updated visual analysis of the panels. Because petrographic analysis was done by Cross, new thin-sections of the Carrara marble panels were not created. The microstructure of Carrara marble is also well characterized in various literature sources.

An initial examination of the characteristics of the Carrara marble samples was conducted prior to treatment application and the testing program. Each panel is 15" x 4" x ¾" in size. The dimensions follow the specifications outlined in both the NT BUILD 499 bowing potential test and ASTM C880 flexural strength testing standards. While thin marble panels found on building façades and used in construction are much larger in size, the dimensions were chosen based on space restrictions and the logistics needed for the testing program. By minimizing the size of the panels tested, a greater number and variety of treatments could be tested.

Cross (2005) characterized the microstructure of the Carrara marble used for both theses. Because the thin-sections could not be found, the following analysis has been taken from Cross (2005, 51):

- The sample panels of Carrara marble have a low porosity, with pores ranging between 0.0125 and 0.025 mm in width
- The calcite grains are homogeneous in size (approximately 0.2 mm in width), with straight grain boundaries
- The grains are sub-rounded with no relative orientation

The above conditions give the Carrara marble sample panels a granoblastic texture. The thin sections used in Cross (2005) were stained with Alizarin red to indicate the presence of calcite; the staining showed no accessory minerals (fig. 20, 21).

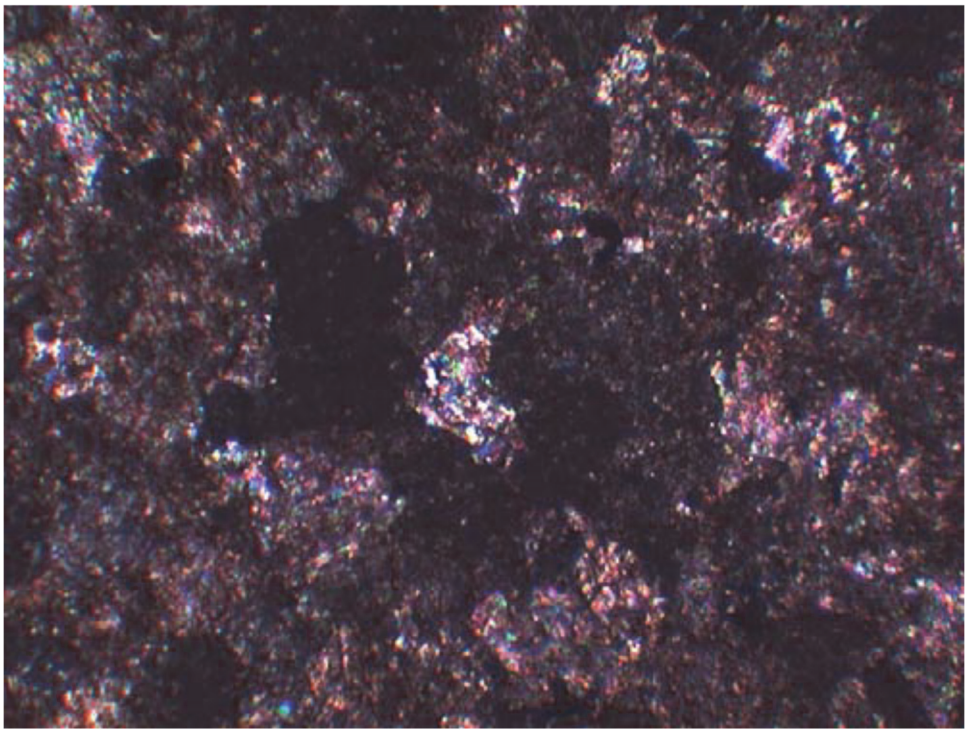

Figure 20: Carrara marble thin section at 10x magnification with an accessory plate (Source: Cross 2005, 52).

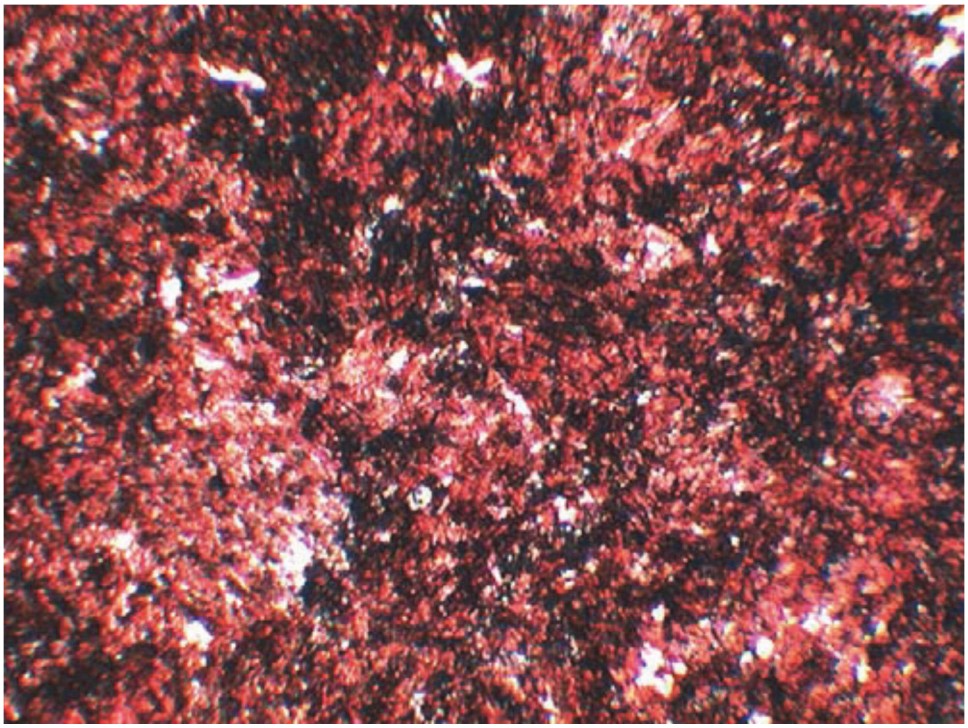

Figure 21: Carrara marble thin section at 10x magnification stained with allzarin red (Source: Cross 2005, 52).

3.1.1 Visual Analysis

The Carrara marble tested in the thesis is white (Munsell color 5PB-9/1) with medium gray veining (Munsell color 10PB-6/1) (fig. 22). The veining is inconsistent across the 15 panels that will be tested, but the coloration of the marble is consistent. Due to the age of the panels, and the method of storage, some of the panels show slight yellow discoloration on the edges. Because all of the panels are the same age and have been stored in the same manner, this was not considered to be a factor that will influence the bowing potential and eventual flexural strength of the sample panels.

Figure 22: Carrara marble panels before testing (Source: D. Pape 2017).

The white Carrara marble is relatively soft with a hardness of 3 out of 10 on the Moh's scale. One face of the marble panel has a polished side, while the other faces are unpolished with a slight roughness. There are a couple of scratches and indentations on the polished face of the stone, but these are likely due to the age of the panels and wear from improper storage.

3.2 Analysis of Rapidry DM 50-75™

Beyond the information provided by the material data sheet and the safety data sheet, certain properties of the Rapidry DM 50-75™ material were tested to ensure its compatibility as part of a FRCM system. Calcium sulfate is listed as a component of the dry mix, presumably to retard set, it could potentially cause problems by introducing soluble

gypsum salts into the masonry. This could potentially add a secondary condition to the system that is unwanted. Although the product is listed as not forming a vapor barrier when the mortar cures, the entire system was tested to determine the separate component's compatibility as a system.

3.2.1 Water Vapor Transmission Tests

In order to perform water vapor transmission testing, three marble disks were cored from a remaining sample panel using a diamond coring bit. A thin layer of Rapidry DM 50-75™ was applied to the reverse face of the marble disk, followed by a fully saturated piece of the carbon fiber fabric. After ensuring key formation, another layer of the adhesive mix was applied. This system cured for 48 hours, followed by 24 hours in the oven. The weight of the system – wrapped with electrical tape to ensure a tight fit in the disposable beaker – was then weighed (M_d). The weight of the disposable beaker (M_b) was also recorded. The beaker was then filled with 70 mL of deionized water, and then weighed (M_{bw}). The marble disk wrapped in electrical tape was then placed in the beaker, and the entire system was sealed with paraffin wax. This system was then weighed (M_a) and placed in the desiccator. The system was weighed after 5, 15, 30 and 60 minutes, and then every 24 hours for the following two weeks (M_n). A graph was created, plotting the weight versus the elapsed time. A straight line of best fit was added, ensuring that the line went through at least six entry points – the slope of the line gives the rate of water vapor transmission. Water vapor transmission (WVT) was calculated using the following formula:

$$WVT = G/tA$$

Where: G = weight change ($M_a - M_n$)
t = time (hours)
G/t = slope of the straight line (g/h)
A = test area (ft^2)
WVT = rate of water vapor transmission ($g/(h/ft^2)$).

Following two weeks of measurement, the marble disks (A, B and C) had a water vapor transmission rate of 0.00137, 0.00157 and 0.00098 $g/(h/ft^2)$ – respectively – with an average of 0.00131 $g/(h/ft^2)$. The system lost weight over the course of testing, showing that water vapor was moving through the reinforced marble system from the water sealed in the beaker into the desiccator chamber. The cementitious adhesive used as part of the system has a tested water vapor transmission rate of 41 perms (Dryvit 2017). As a system, the Rapidry DM 50-75™ likely does affect the water vapor transmission of the Carrara marble, but it is still allowing the movement of moisture through the system as a whole.

The Marble Institute of America lists the water vapor permeability of marble as a range from 0.324 – 4.460 Perm-inch (MIA 2016, 7-17). Water vapor transmission can be converted to permeance by calculating the change in vapor pressure (mmHg). The permeance of the calculated average water vapor transmission is 0.00015 perms. The average permeability of a sample can be calculated by multiply permeance by the sample's thickness. For the samples tested in this thesis, the average permeability would be 0.0003 perm-inch. When this average permeability is compared to the range of water vapor permeability of marbles created by the Marble Institute of America, the reinforcement system has severely lowered the permeability of the marble.

3.2.2 Soluble Salts Testing

The soluble salt content of the Rapidry DM 50-75™ adhesive was tested using quant strips for various salt types. Because calcium sulfate is listed as a component, the analysis of the sulfate concentration was the most important. The concentration of nitrates and chlorides was also tested. Quant strips give the concentration in mg/l, and the test involves dipping the strips in the dry mortar mix dissolved in deionized water. The color of the strip after a certain amount of time is compared to a diagram on the bottle, giving the concentration. Rapidry DM 50-75™ had little to no nitrates and chlorides, shown by no color change. The mortar mix, however, does have a sulfate concentration greater than 1600 mg/l. Because of this result, more testing should be done into the salt content of the cementitious adhesive before the treatment method is conclusive.

3.3 Application of Treatment

Before the mechanical treatment was applied to the non-polished face of the marble sample panels, the face of the substrate was cleaned to remove any dust or particles that could be of the surface. The carbon fiber fabric was cut down to slightly larger than the dimensions of the marble panels, and was set to the side. For each panel, 200 grams of the dry Rapidry DM 50-75™ powder was fully mixed with 50 mL of deionized water – by hand with a trowel for at least three minutes – until the resulting mortar was completely smooth with no lumps. The carbon fiber fabric piece associated with the panel was then fully saturated with deionized water. Half of the mortar mix was then applied to the substrate, creating an even layer of mortar on the reverse face of the marble panel. The carbon fiber fabric was

then placed on the mortar layer, pressing down on the mesh until keys of the mortar form through the openings in the mesh. While the lower layer of mortar was still wet, a second layer of mortar was applied – the other half of mixed mortar. This was also applied in a manner to ensure that it formed an even layer. These steps were repeated for each of the panels tested (fig. 23). Each panel was treated separately to ensure uniformity across the samples tested.

Figure 23: Application of FRCM system to the marble panels (Source: N. Declet 2017).

After allowing the sample panels to cure for a full 48 hours, photographs of the samples were taken to create a base-line for the visual analysis of the surface of the marble. These photographs were compared to later visual observations to document change over

time to determine the extent of the deformation or deterioration brought on by the bowing potential and flexural strength tests.

3.4 Bowing Potential

Because only one testing apparatus remained in storage at the Architectural Conservation Lab from Cross (2005), two other systems had to be constructed in order to complete the bowing potential testing for this thesis. The remaining apparatus was measured, and pieces of plywood were cut down to size. Two additional apparatus systems were constructed following these measurements. Because of the two heat lamps per apparatus, each had to be wired in order to provide electricity to the system. This involved linking two light sockets from the bottom of the central rail to a metal electrical box, which was then linked to a grounded extension cord. Non-corrosive pans were filled with a layer of glass rods and water to provide moisture to the system (fig. 24).

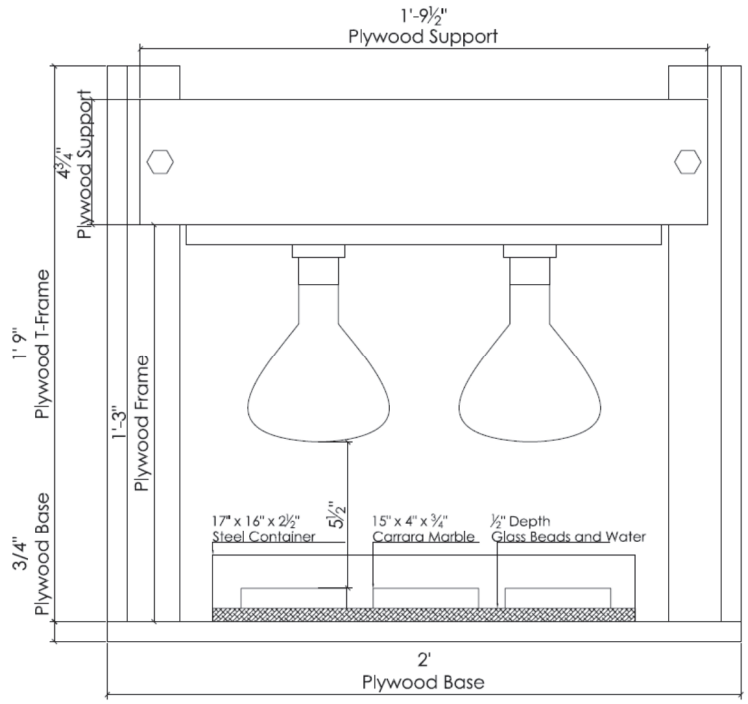

Figure 24: Measurements of the testing apparatus constructed based on the measurements from Cross (2005, 42).

Each apparatus held three marble sample panels. The bow of each sample panel was measured once a day, before the heat lamps were turned on. Bow measurement involved matching three marked points on each sample panel to the two metal beams and central gauge. The marble sample panels were subjected to 40 cycles of the bowing potential testing – consisting of four hours of heat and a minimum of 16 hours of ambient temperature, while maintaining a consistent water level in the pan. The change in bow measurement was graphed compared to the number of cycles.

The magnitude of bowing is calculated by dividing the difference of the first gauge reading and the final reading by the length between the two metal beam supports. The following formula,

$$\tau = \Delta h/L$$

Where: τ = magnitude of bowing (mm/m)
Δh = change in height in mm (after 40 cycles)
L = length between the supports (9 inches, or 0.2286 meters)

is used to calculate the magnitude of bowing.

During testing, the measurements were not consistent, and did not always show an increase in bowing magnitude. To attempt to make the testing as consistent as possible, the readings were taken at the same time every day in order to follow the same trajectory of heat and cool cycles. Some discrepancies in the data might come from the variable ambient temperature in the testing room, as the outside weather over the course of testing ranged greatly influencing the temperature and humidity of the testing room. Because of the variable temperature, the marble panels might not have been subjected to the same range in temperatures for each cycle.

3.4.1 Results of Testing

Following the 40 cycles, the control panel had a bowing magnitude of 0.89 mm/m, while the treated panels had an average bowing magnitude of 3.74 mm/m. The control panel reached a bowing magnitude of 2.42 mm/m, but the magnitude dropped following that reading at the 24th cycle and plateaued at 0.89 mm/m magnitude at the 32nd cycle. Sample C2, which was only subjected to 20 cycles, had a final bowing magnitude of 1.96 mm/m. The panels that had been previously bowed and then treated before further bowing potential testing (CFR1&2) had an average bowing magnitude of 1.19 mm/m after 20 cycles of testing, lower than that of the control panel.

Samples	Bowing Magnitude at 20 Cycles (mm/m)	Bowing Magnitude at 40 Cycles (mm/m)
C1	1.70	0.89
Average of A1-5	3.63	3.74
C2	1.96	~
Average of CFR1-2	1.19	~

Table 1: Bowing Magnitude

As seen in the graph of the bowing magnitudes, the readings were unpredictable and did not consistently grow over the course of the testing (fig. 25). There are significant dips in the graph over the course of the testing, but the dips in the bowing magnitude typically occur at the same testing cycle across all the samples. Because of the small changes in the measurements made with the bow meter, an overall net-positive change in the concavity of the marble panels can be seen.

The treated marble panels could have bowed more than the untreated panels for several different reasons. The FRCM system potentially could have absorbed more water than the untreated panels, leading to different levels of the expansion and contraction of the back face of the marble panel. The treatment itself could have also contributed to the contraction of the back face of the marble panel. As marble panels bow, one face expands and the other face contracts due to unequal thermal expansion of the calcite grains. Because the FRCM system was effectively bonded to the back face of the marble panels, it could have contributed to the natural contraction of that face of the marble panel.

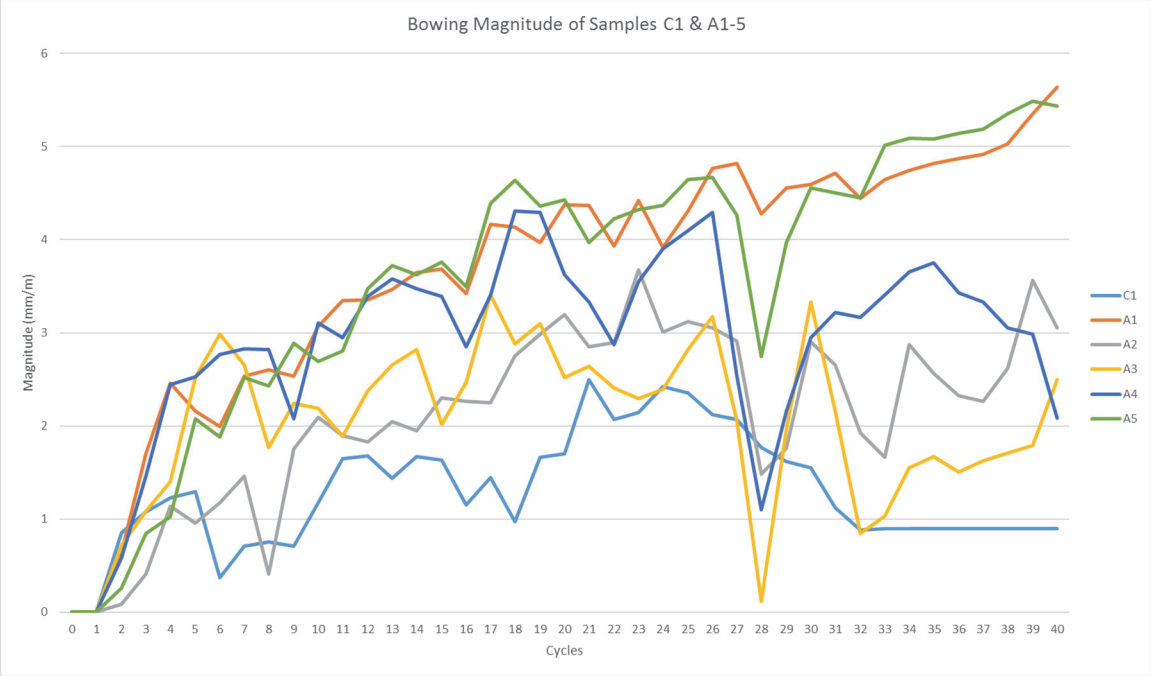

Figure 25: The above graph shows the bowing magnitude of the marble panels tested during the 40 cycles of the NT BUILD 499 testing procedure. It indicates the variability of the test.

Over the course of bowing potential testing, the visual appearance of the marble panels changed due to the testing parameters (fig. 26, 27). The tops and sides of some panels showed discoloration, mainly yellow to sandy in color. This was probably from the combination of a free-water source and the proximity of the heat lamps. On a couple of the treated panels, the adhesive system also discolored, changing from grey to brown. This was mainly found at the edge of the panel. Some of the panels also began to have a "sugary" substance on the top-face of the panel half-way through testing. The following photographs show the changes to the visual appearance of the marble panels after 20 cycles and after 40 cycles.

When compared to the results from Cross (2005), the difference between the magnitude of displacement of the untreated and treated panels was much greater in this round of testing. In Cross (2005), the untreated panels bowed 0.029 inches and the carbon fiber strap treated panels bowed 0.023 inches. Following testing, the panels tested in this thesis bowed 0.008 inches and an average of 0.219 inches, untreated versus treated respectively. Because the marble panels used in both rounds of testing were from the same source, the measurements either show the variability of Carrara marble or sources of error in the bowing potential testing. Based on the results of this testing, the results of the flexural strength tests were not predicted to show an increase in strength of the treated panels because as bowing magnitude increases the flexural strength of marble tends to decrease.

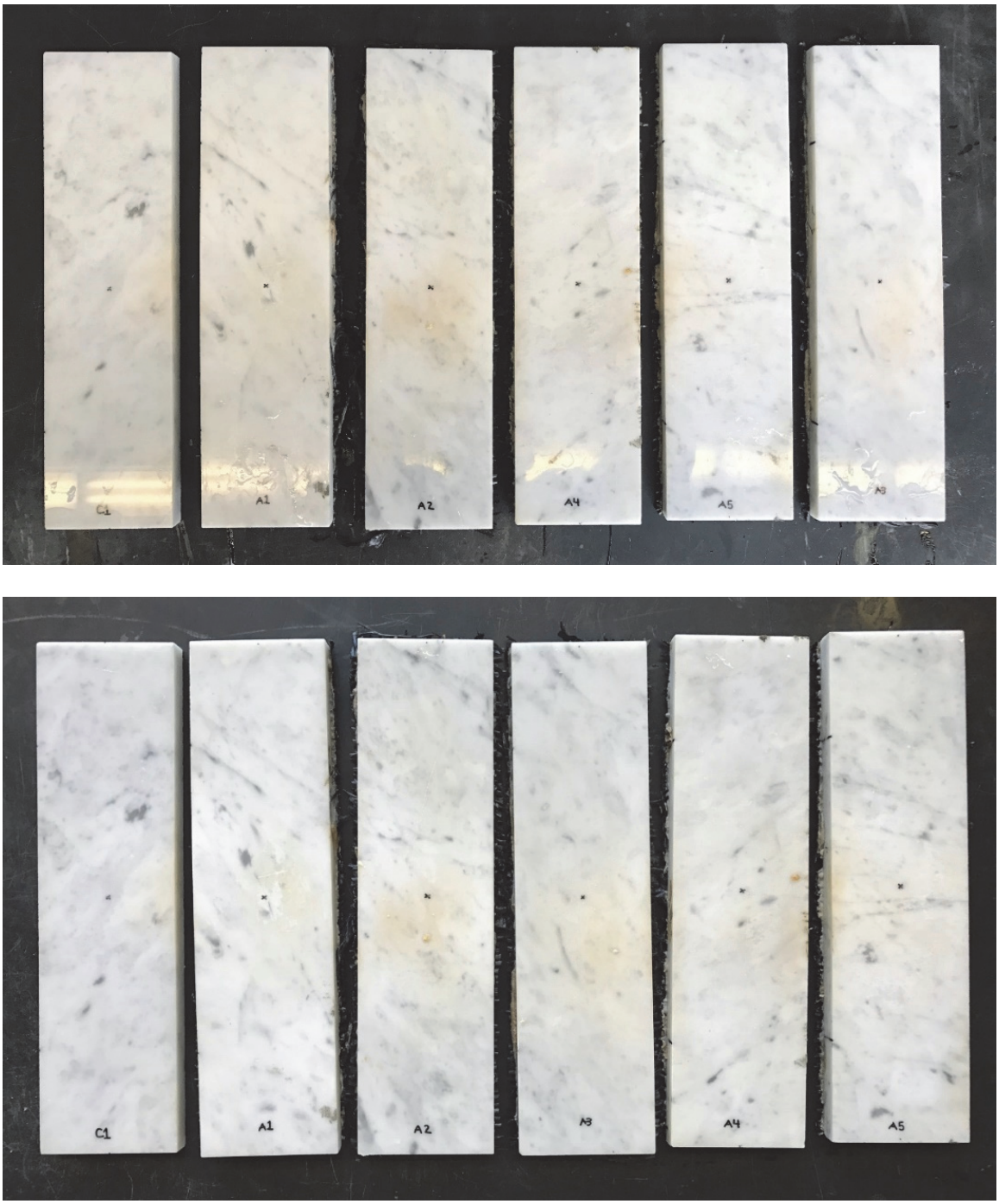

Figure 26 and Figure 27: The marble panels after 20 cycles (top) and 40 cycles (bottom). Both show yellow discoloration and visible bowing of the treated panels (A1-5) (Source: D. Pape 2017).

3.5 Flexural Strength

After the bowing potential testing was completed, the flexural strength of certain panels was tested. The testing followed ASTM C880, which included a 4-point bending procedure. Testing was conducted at the Laboratory for Research on the Structure of Matter at the University of Pennsylvania with help from Dr. Alex Radin. Before testing could be conducted, the 4-point bending apparatus needed to be assembled on the machinery. In the test, the marble panel rests on two supports at either end of the panel. Two additional supports rest on the top of the panel, resting approximately a third of the length of the panel from the edge. The load is applied to the center of the panel, above the upper two supports (fig. 28). After the apparatus was assembled and key measurements were made, the testing proceeded.

The control panels (C1 & C3) were tested first, in order to establish a baseline of when untreated panels were likely to break. These numbers were also later compared to the results found in Cross (2005), and other scholarly work on the typical flexural strength of Carrara marble. Following the control panels, treated panels that were cycled and uncycled for bowing potential were tested. The panels tested were the following: A1, A3, A6, CFR1 and CFR2. These numbers were later compared to the results found in Cross (2005) of the marble panels with a carbon fiber straps and polypropylene honeycomb.

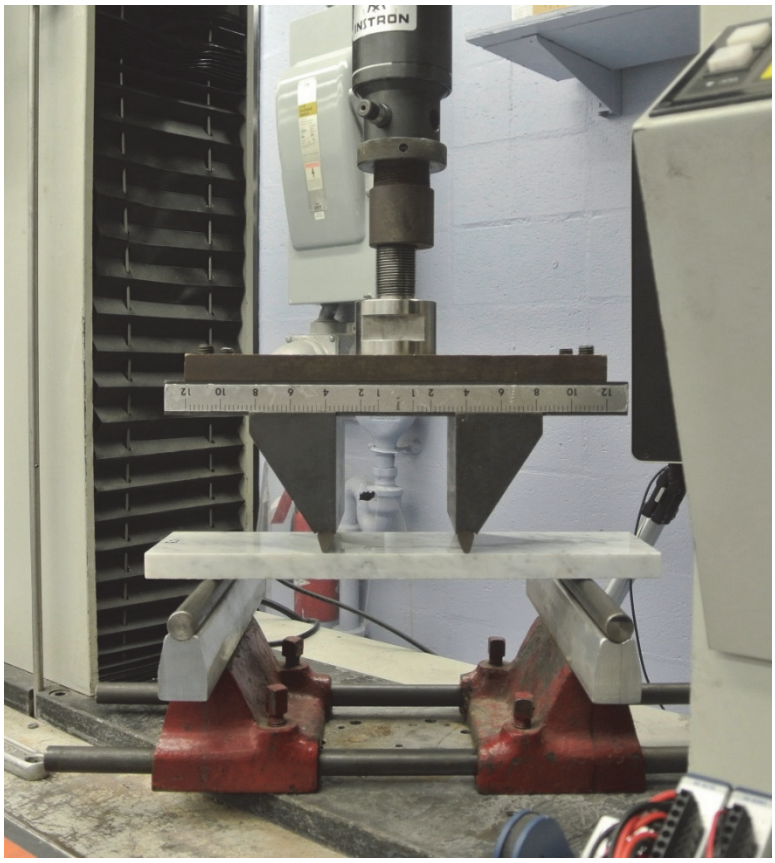

Figure 28: The set-up for 4-point bending to test for flexural strength (Source: D. Pape 2017).

After the panel was loaded into the testing apparatus, a uniform load in compression at 25 lbs/V and displacement at 0.1 in/V. Because of the added weight of the testing apparatus, an additional 30 pounds needed to be added to the failure loads. Each testing procedure was filmed to be able to determine the failure point visually, and to also compare the numerical results of the 4-point bending tests to when microcracks began forming on the surface of the edge of the marble panels.

There were two main failure modes, (1) complete failure and (2) the development of cracks through the entire depth of the marble panel. At both points, the load being

added to the apparatus began to decrease. Because not all of the panels had a complete failure resulting in separate pieces of the marble panel, the video of the testing proved helpful to determine where and when the panel failed mechanically. During testing, the computer attached to the testing machinery recorded load and displacement data, which was transferable as a .txt file into Microsoft Excel in order to interpret the data and to determine at what load the marble panels failed.

Figure 29: During the 4-point bending test of a treated panel. The FRCM system remains attached to the panel following cracking (Source: D. Pape 2017).

3.5.1 Results of Testing

During 4-point bending tests, the untreated panels failed at loads more 200 pounds less than the treated panels. The untreated panels completely failed, with C1 and C3 breaking into three and two separate pieces respectively. While weight was being added to the testing apparatus, the fiber reinforced cementitious matrix (FRCM) treatment system remained bonded to the marble panel substrate, effectively holding the panel together after the panel had cracked through the full depth (fig. 29). While the Rapidry DM 50-75™ did become brittle and become unattached at the locations of the cracks through the marble panel, the loads did not reach a weight to break the carbon fiber fabric.

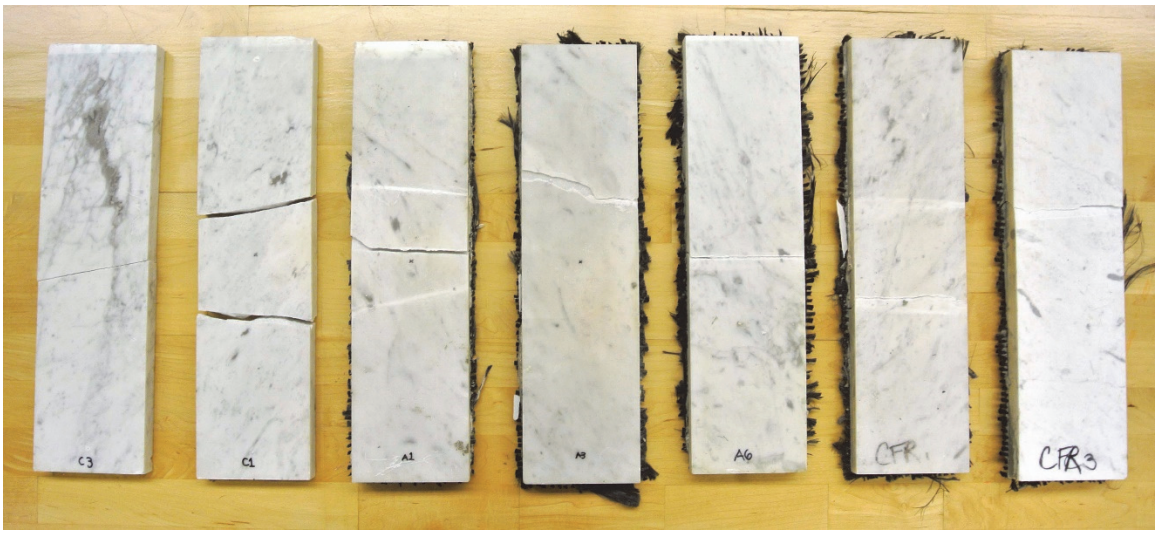

Figure 30: Carrara marble panels after bowing potential tests and 4-point bending tests. The image shows the different failure mechanisms caused by the 4-point bending tests (Source: D. Pape 2017).

After the 4-point bending tests were completed, the flexural strength of each panel was calculated. This was done using the following formula:

$$\sigma = (3WL)/(4bd^2)$$

Where: σ = flexural strength (pounds per square inch)
W = maximum load (pounds)
L = span (inches)
b = width of panel (inches)
d = depth of panel (inches)

This formula and the collected measurements were used to calculate the following flexural strengths of the marble panels tested. The maximum load was determined by graphing the time versus load graphs, and visually determining where the load began to decrease instead of increase. Dips in the graph of time versus load indicate where the panel failed or when microcracks began to form. Both control panels (C1 & C3) failed below 300 lbs, while microcracks began forming in the treated panels between 400 and 500 lbs. When the marble panel cracked through the full depth, the time versus load dropped drastically; this is especially evident in the A6 series (fig. 31).

As the treated panels failed, the failure mode was not a clean break, but rather a slow progression, at times cracking diagonally through the stone or leading to a greater failure at the surface. In panels where the cracks were not extremely evident, the top of the marble panel appeared to be bent, and the break opened fully when the panel was moved from the testing apparatus. The breaks on the untreated panel were clean in comparison. At the face of the break in both the treated and untreated panels, the marble appears granular and has a rough texture (fig. 32).

Samples	Maximum Load (lbs)	Flexural Strength (psi)
C1	239	1195
C3	260	1300
A1	680	2498
A3	825	3031
A6	652	2395
CFR1	718	2638
CFR3	475	1744

Table 2: Flexural Strength testing

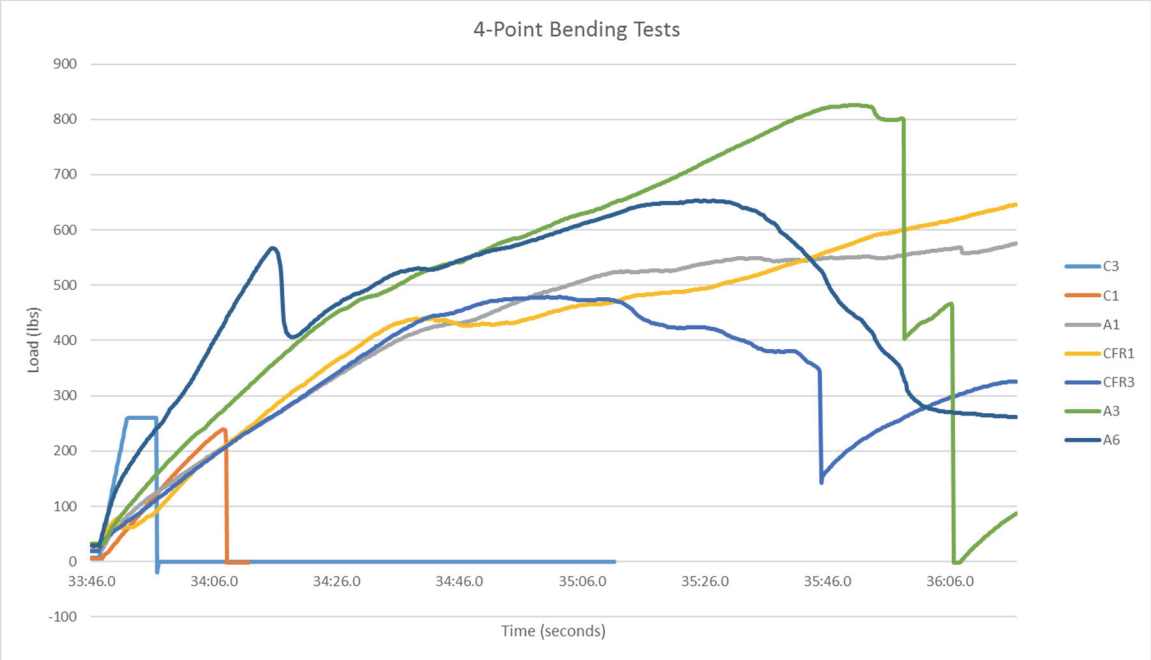

Figure 31: The above graph indicates the loading pattern that was created during the 4-point bending procedure. The graph indicates failures in the panels (Source: D. Pape 2017).

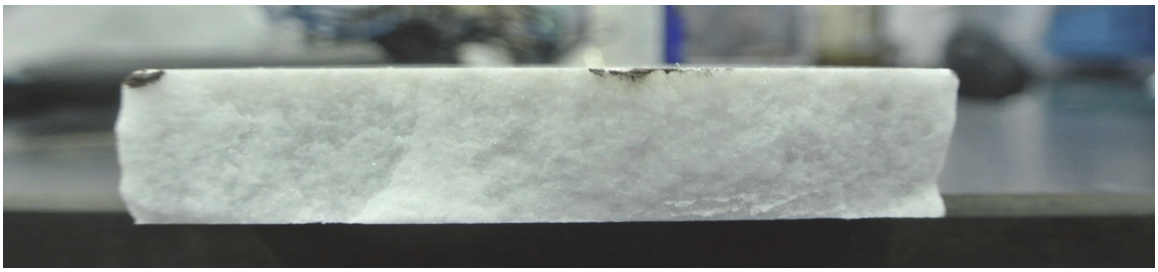

Figure 32: Rough surface of the break of an untreated panel (Source: D. Pape 2017).

Following the 4-point bending procedure, the FRCM treatment remained bonded to the marble substrate; it only failed at the locations of the cracks in the marble panel. As microcracks began forming in the marble, the FRCM treatment continued to hold the panel together (fig. 33). This shows the effectiveness of the system at increasing the flexural strength of the marble. Because the system continued to hold the panel together after cracking, it could potentially be a good treatment method in small-scale applications where the system could be easily monitored.

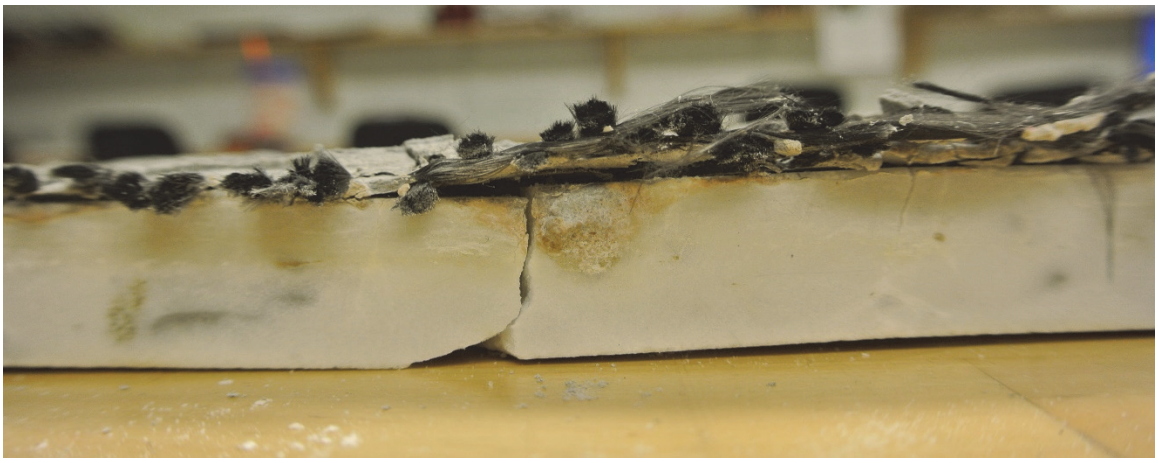

Figure 33: Formation of cracks through the treated marble panels. The image shows that the FRCM system remained bonded to the marble substrate in the areas neighboring the cracks (Source: D. Pape 2017).

3.6 Limitations

Because the testing program used for this thesis closely followed the accepted standards of testing, the only variations came from differences in the suggested equipment and what was available in the lab. The bow meter gauge was the greatest change from the testing procedure described in the NT BUILD 499 standard. The measurement procedure used in the thesis was the same as in Cross (2005), who developed this method of measurement as a way to minimize the cost associated with the recommended bow meter gauge used by the TEAM program and the NT BUILD 499 standard. The results of this testing were comparable to those in Cross (2005), making the measurement method acceptable. Variations between the two testing procedures could be from the differences in ambient temperature and the reading times, which affect all the sample panels, nulling the fluctuations.

Flexural strength testing followed the procedure outlined in ASTM C880 almost exactly because the testing machinery was all available at the LSRM facility. The results associated with the testing were what was expected based on the literature available on the loss of flexural strength associated with bowing of marble panels. The FRCM system, which has a high tensile strength because of the carbon fiber fabric, increased the flexural strength of the marble panels as expected. Because the treatment was applied to all of the marble panels in the same manner, the results of the testing of the treated panels can be compared.

CHAPTER 4: CONCLUSION

4.1 Final Analysis

The results of this research were inconclusive in creating a treatment method for bowed marble panels. During bowing potential testing, the marble panels with the FRCM treatment reached a greater bowing magnitude than the panels without an applied treatment. This could have been because of sources beyond the control of the testing parameters, but the FRCM system could have attributed to the bowing potential by constraining the face of the marble panel that did not expand at the same rate as the outer face. Potentially, the tensile strength of the carbon fiber fabric, the bond between the marble panel and the Rapidry DM 50-75™ adhesive, and the water absorbance of the system exacerbated the bowing potential of the Carrara marble panels.

It was expected that the FRCM system would increase the flexural strength of the marble panels because of the material properties of the individual components of the system, but not at the levels determined by the 4-point bending tests. The interior face of the breaks of the treated and untreated panels had different appearances, with the untreated marble having a more granular texture than that of the treated panels. There were minimal differences between the pattern of both bowing and the flexural strength of the panels that had been bowed for 40 cycles and then an addition 20 cycles after treatment to the unbowed panels that were treated and then bowed for 40 cycles. Overall, all the sample panels increased in bowing magnitude over time, with fluctuations throughout the 40 cycles of testing. The treated panels all exhibited the same failure

mechanisms during 4-point bending tests, involving the development of microcracks before slowly reaching complete failure. This contrasts with the untreated panels which had catastrophic failures when loads were applied.

The results of the two testing procedures suggest two different conclusions. The FRCM system did increase the flexural strength of the bowed marble panels, as seen in the results of the 4-point bending procedure, but the treatment potentially could have exacerbated the bowing magnitude of the Carrara marble panels. Because the treated panels reached a greater bowing magnitude than the untreated panels, the FRCM system could increase the problem caused by environmental hysteresis when used in situ. More testing will need to be done in the lab and in the field before a conclusive treatment for bowed marble panels is determined.

4.2 Alternative Approaches

Moving forward, different materials should be tested as part of an FRCM system to determine which combination of materials will potentially lower the bowing magnitude compared to the results of the bowing potential tests of the treated and untreated Carrara marble panels. This could include non-proprietary mortars and various strengths of carbon fiber fabric. A proprietary cementitious adhesive was used for this thesis because of time constraints and the added material properties from its formulation, but a non-proprietary mortar would lower the cost of the FRCM system, as well as making the treatment more accessible to craft workers. Further testing should also include various mortar compositions that could potentially behavior differently depended on the environmental conditions of

the site and the needs of the project. Multiple marble types should also be tested, because while Carrara marble is the most common type used for thin panel veneers, other marbles are used and testing should show this variation.

Another aspect that should be included in further testing is the effect of the FRCM system on naturally bowed thin marble panels. Research into whether naturally bowed panels can be "unbowed," or flattened. Following flattening, and consolidation to create a homogenous substrate, testing should be done to determine the effectiveness of a FRCM to resist bowing. This treatment protocol could be useful in small-scale applications – like the bowed marble closure tablets at St. Louis I Cemetery in New Orleans – when a longer treatment protocol could be followed.

Although not discussed in this thesis, there are companies that are producing reinforced thin stone veneers which resist the effects of environmental hysteresis. One such company, StonePly Co., offers aluminum honeycomb backed thin veneers in 274 different stone types. Because replacement at times includes thicker marble panels that may bow through environmental hysteresis if not tested properly, replacement with such reinforced thin stone veneers would decrease the chance of secondary deformation and to limit the aesthetic impact of replacement when other materials might be chosen for replacement.

4.3 Next Steps

The bowing of thin marble panels has been included in literature as early as the 1880s, and literature on the topic became more prolific in the 1990s following the early catastrophic failures of entire Post War building façades less than 20 years after construction due to

limited knowledge of the material properties of marble at thicknesses less than two inches. Although the process of environmental hysteresis has been documented and researched, there is currently still not a conservation treatment for bowed marble panels beyond replacement. As the buildings constructed in the Post War era reach 50 years after construction, making the structures eligible for the National Register of Historic Places, a treatment method will become necessary to conserve the historic building fabric. A treatment method that conserves historic building fabric will also help to reduce the loss of carved and detailed thin marble panels that are valued for their aesthetic and historic significance. While the treatment method tested in this thesis did increase the flexural strength of the thin marble panels following induced bowing, more testing needs to be undertaken before a treatment method is conclusive.

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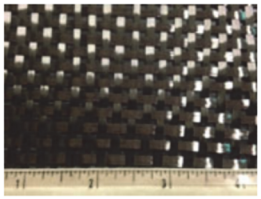
APPENDICES

A: Materials and Suppliers

A.1 Carbon Fiber Mesh
U.S. Composites, Inc.
http://www.uscomposites.com/shortroll.html

9.5 oz x 50 inch - 12K - Plain Weave Carbon Fiber



[Enlarge Photo]

Weight: 9.5osy
Weave: Plain
Tow Size: 12K
Thickness: .021"

Heavy duty plain weave. 12K Tow Size for fast buildup. Very conformable for a 12K fabric.

Thread count:
5 Picks x 5 Picks per inch

Good openness to the weave for easy resin saturation. Only available until we run out.

9.5 oz 2x2 Plain Weave - 50in width
- In Stock -

Cat No.	Description	Price
FG-CF0950	9.5oz x **50"** Width (1 to 4 yards)	**$25.50**/ Yard
Same	5+ Yards	**$23.00**/ Yard
Same	10+ Yards	**$21.50**/ Yard
Same	20+ Yards	**$20.00**/ Yard

A.2 Carrara Marble Panels
Carrara Marble from:
Cava International
2007 Washington Ave.
Philadelphia, PA 19146
(215) 732-0907
www.cavaint.com

A.3 Rapidry DM 50-75™
Manning Materials Corp.
680 Ben Franklin Highway East
Birdsboro, PA 19508
(800) 445-1719
www.manningmaterials.com

RAPIDRY DM™ 50 - 75

DS457

Fast Setting, Dry Mix, Polymer-Modified, Cementitious Adhesive and Base Coat

Description

Rapidry DM 50-75 is a fast setting, dry mix, polymer-modified, cementitious adhesive and base coat for use with Dryvit systems.

Uses

Rapidry DM 50-75 is used to adhere expanded polystyrene insulation board to acceptable substrates and to embed reinforcing mesh as part of the base coat for Dryvit systems. It is specifically engineered to use when job site temperatures will be between 50 °F (10 °C) and 75 °F (24 °C). It dries faster than traditional EIFS adhesives and base coats while providing an adequate working time. Use of Rapidry DM 50-75 is not recommended if temperature is to exceed 75 °F (24 °C). The rapid cure time of Rapidry DM 50-75 permits two installation steps to be completed during one workday, i.e., insulation board installation and rasping or base coat and finish application.

Coverage

Approximately 55 ft² (5.1 m²) of surface area per 45 lb (20.4 kg) bag, including adhesive and base coat layers. For adhesive only, 100 ft² (9.3 m²); for base coat only, 120 ft² (11.1 m²).

Properties

Working Time - After mixing, the working time of Rapidry DM 50-75 is approximately 30 minutes. The higher the temperature the shorter the working time.

Drying Time – Drying time of the Rapidry DM 50-75 mixture is dependent on the air temperature and relative humidity. See chart for approximate drying time under various conditions. Protect work from rain during the drying time. Being a cementitious product, the Rapidry DM 50-75 mixture develops full strength in 28 days. When used to bond expanded polystyrene insulation board to an acceptable substrate, enough time must elapse to allow Rapidry DM 50-75 to form a positive bond. The installed insulation board should not be disturbed until adequate bond has developed. When used as a base coat, finish can be applied after 4 hours under average drying conditions [70 °F (21 °C), 55% RH].

Approximate Drying Time of Rapidry DM 50 – 75 Under Various Conditions

Adhesive		
Temperature/Humidity	**Traditional Cementitious Adhesive**	**Rapidry DM 50-75**
50 °F (10 °C)/90% RH	24 hours	2 1/2 hours
60 °F (16 °C)/55% RH	20 hours	2 hours
70 °F (21 °C)/55% RH	16 hours	1 1/2 hours
75 °F (24 °C)/55% RH	12 hours	1 hour
Base Coat		
Temperature/Humidity	**Traditional Cementitious Base Coat**	**Rapidry DM 50-75**
50 °F (10 °C)/90% RH	24 hours +	7 hours
60 °F (16 °C)/55% RH	24 hours	5 hours
70 °F (21 °C)/55% RH	24 hours	4 hours
75 °F (24 °C)/55% RH	20 hours	3 hours

Testing Information

For individual test data on this product's properties, refer to the chart included with this document.

Application Procedure

FOR COMPLETE APPLICATION INSTRUCTIONS, REFER TO THE APPROPRIATE DRYVIT SYSTEM APPLICATION INSTRUCTIONS.

Job Conditions – Rapidry DM 50-75 is designed for applications in the temperature range of 50-75 °F (10-24 °C). Care must be taken to ensure that air and surface temperature is between 50°F and 75 °F (10 °C - 24 °C), and such conditions must be maintained during curing. The temperature of Rapidry DM 50-75 material and water must be at or below 75 °F (24 °C) prior to mixing. Higher temperatures will shorten the pot life.

Temporary Protection – Shall be provided at all times until the adhesive, base coat, finish and permanent flashings, sealants, etc. are completed to protect the wall from inclement weather and other sources of damage.

Acceptable Substrates:

- Exterior grade gypsum sheathing meeting ASTM C 1396 (formerly C 79) requirements for water-resistant core or Type X core
- Exterior sheathing having a water-resistant core with fiberglass mat facers meeting ASTM C 1177
- Exterior fiber reinforced cement or calcium silicate boards
- Unglazed brick, cement plaster, concrete or masonry
- Galvanized expanded metal lath 2.5 or 3.4 lbs/yd² (1.4 or 1.8 kg/m²) installed over a solid substrate

Surface Preparation:

- Surfaces must be above 50 °F (10 °C) and must be clean, dry, structurally sound and free of efflorescence, grease, oil, form release agents and curing compounds.
- The substrate shall be flat within 1/4 in (6.4 mm) in a 4 ft (1.2 m) radius.

Mixing

Pail Mixing – One 45 lb (20.4) bag of Rapidry DM 50-75 will produce approximately 5 gal (19 L) of Rapidry DM 50-75 mixture. To a clean Dryvit 5 gal (19 L) pail, add 5.5 qt (5.2 L) of clean potable water. As an alternative on the inside of the Dryvit 5 gal (19 L) pail, draw a horizontal line which measures 3 13/16 in (97 mm) from the base of the pail

and fill with water. Add the Rapidry DM 50-75 slowly while mixing using a "Twister" paddle or equivalent mixing blade, powered by a 1/2 in (12.7 mm) drill, at 500-1200 rpm. **NOTE: A minimum 7 amp drill works best for Portland cement based materials.** Thoroughly mix until uniformly wetted, adjusting consistency with a small amount of water or Rapidry DM 50-75 material. Let set for 5 minutes. Retemper adding a small amount of water if necessary. Material must be free of lumps before using.

Mortar Mixer – Rapidry DM 50-75 can be mixed in a mortar mixer by first adding 5.2 L (5.5 qt) of clean potable water for each 45 lb (20.4 kg) bag of Rapridry DM 50-75. Add the Rapidry DM 50-75 while the mixer is running. Mix for 3-5 minutes, shut mixer off for 5 minutes, then run mixer for another 2-3 minutes to break the set adjusting consistency with a small amount of water or Rapidry DM 50-75. Material must be free of lumps before using. The pot life is approximately 30 minutes depending on temperature.

Application

Adhesive – For application over **sheathing substrates**, use a stainless steel notched trowel with notches measuring 3/8 in (9.5 mm) wide, 1/2 in (12.7 mm) deep spaced 1 1/2 in (38 mm) apart. Apply the Rapidry DM 50-75 mixture on the back side of the insulation board and scrape the excess adhesive from between the adhesive beads. The adhesive beads shall be applied so that they run vertically when the insulation board is placed on the wall.

For application over **non-sheathing substrates**, the notched-trowel application as described above is acceptable or a ribbon and dab application may be used.

With a stainless steel trowel apply a ribbon of the Rapidry DM 50-75 mixture 2 in (51 mm) wide x 3/8 in (9.5 mm) thick around the entire perimeter of the insulation board. Place eight dabs of the Rapidry DM 50-75 mixture 3/8 in (9.5 mm) thick by 4 in (102 mm) in diameter approximately 8 in (203 mm) on center to the interior area. **CAUTION: Do not install Rapidry DM 50-75 mixture directly on the substrate.** Immediately place the insulation board on the substrate, ensuring that no Rapidry DM 50-75 mixture gets into board joints. Do not allow the Rapidry DM 50-75 mixture to form a skin before positioning the insulation board on the substrate as it will affect the bond strength.

Base Coat – For base coat application, all insulation board irregularities greater than 1/16 in (1.6 mm) must be sanded flush. Apply the base coat to the entire surface of the insulation board. Fully embed the Dryvit reinforcing mesh in the wet base coat troweling from the center to the edge of the reinforcing mesh so as to avoid wrinkles. The reinforcing mesh shall be continuous at all corners and lapped or butted in accordance with Dryvit's recommendations. The overall minimum base coat thickness shall be sufficient to fully embed the reinforcing mesh. The recommended method is to apply the base coat in two applications. All areas requiring higher impact resistance shall be detailed on the plans and described in the contract documents. The application shall be installed in accordance with Dryvit's recommendations.

Clean Up – Clean tools with water while the Rapidry DM 50-75 mixture is still wet.

Storage

Rapidry DM 50-75 bags must be protected from moisture and weather. The bags shall be stored off the ground in a cool, dry location, out of direct sunlight. If the RapidDry is warm or hot, the pot life of the RapidDry mixture will be reduced.

The shelf life is 1 year from date of manufacture when properly stored in unopened bags.

Cautions and Limitations

- Avoid applying RapidDry in direct sunlight. Always work on the shady side of the wall or protect the area with appropriate shading material.
- Clean potable water may be added to adjust workability. Do not overwater. Warm water will accelerate the set.
- Rapidry DM 50-75 shall not be used to adhere EPS directly to wood based substrates.
- Mixing paddles and pails must be clean. Contamination from previous mixing will lead to a short pot life.
- Wear protective eyewear and clothing since the product contains cement, which can cause irritation.

Technical and Field Service

Available on request.

Rapidry DM™ 50 – 75 Testing			
Test	**Test Method**	**Criteria**	**Results**
Surface Burning Characteristics	ASTM E 84	ICC and ANSI/EIMA 99-A-2001 Flame Spread <25 Smoke Developed <450	Passed
Water Vapor Transmission	ASTM E 96 Procedure B	ICC: Vapor Permeable No ANSI/EIMA Criteria	41 Perms
Accelerated Weathering	ASTM G 23 (Carbon Arc)	ICC: 2000 hours: No deleterious effects[1]	2000 hours: No deleterious effects[1]
Freeze-Thaw Resistance	ASTM E 2485 (formerly EIMA 101.01)	ANSI/EIMA 99-A-2001 60 cycles: No deleterious effects[1]	60 cycles: No deleterious effects[1]
	ASTM E 2485/ICC-ES Proc: ICC ES (AC219*)	No deleterious effects[1] after 10 cycles	Passed – No deleterious effects[1] after 10 cycles
Water Resistance	ASTM D 2247	ICC and ANSI/EIMA 99-A-2001 14 days: No deleterious effects[1]	14 days: No deleterious effects[1]
Tensile Bond[2]	ASTM C 297/E 2134 (formerly EIMA 101.03)	ICC and ANSI/EIMA 99-A-2001 Minimum 15 psi (104 kPa) – substrate or insulation failure	>15 psi (104 kPa)
Water Penetration	ASTM E 331	No water penetration beyond the inner-most plane of the wall after 2 hours at 6.24 psf (299 Pa)	Passed

1. No cracking, checking, rusting, crazing, erosion, blistering, peeling, or delamination when viewed under 5x magnification.
2. Sample consists of 1" EPS adhered to various substrates
* AC219 – Acceptance Criteria for EIFS

Dryvit Systems, Inc.
One Energy Way
West Warwick, RI 02893
800-556-7752
www.dryvit.com

Printed in USA. Issued 10-04-16

SAFETY DATA SHEET

Revision Date 22-Mar-2017
Version 1

1. Identification of the substance/mixture and of the company/undertaking

1.1 Product identifier

Product name Rapidry DM 50-75
Product code 023036

1.2 Relevant identified uses of the substance or mixture and uses advised against

Recommended Use Restricted to professional users
Restrictions on use No information available

Uses advised against Not suitable for use in homeworker (DIY) applications

1.3 Details of the supplier of the safety data sheet

Supplier
Dryvit Systems, Inc.
One Energy Way
West Warwick, RI 02893
(401) 822-4100

E-mail Address ehs@dryvit.com

1.4 Emergency telephone number

Emergency telephone number
Chemtrec: +1 703-527-3887 ex-USA
Chemtrec: 1-800-424-9300 USA

2. Hazards identification

2.1 Classification of the substance or mixture

GHS Classification in accordance with 29 CFR 1910.1200

Skin corrosion/irritation	Category 2
Serious eye damage/eye irritation	Category 1
Skin sensitization	Category 1B
Carcinogenicity	Category 1A
Specific target organ toxicity (single exposure)	Category 3 - (H335)

2.2 Label elements

Signal Word
Danger

Hazard Statements

Causes skin irritation
Causes serious eye damage
May cause an allergic skin reaction
May cause cancer
May cause respiratory irritation

Precautionary Statements - Prevention
Obtain special instructions before use
Do not handle until all safety precautions have been read and understood
Use personal protective equipment as required
Wash face, hands and any exposed skin thoroughly after handling
Avoid breathing dust/fume/gas/mist/vapors/spray
Contaminated work clothing should not be allowed out of the workplace
Keep/Store away from clothing/ combustible materials
Use only outdoors or in a well-ventilated area

Precautionary Statements - Response
If exposed or concerned: Get medical advice/attention
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing
Immediately call a POISON CENTER or doctor/physician
IF ON SKIN: Wash with plenty of soap and water
Take off contaminated clothing and wash before reuse
If skin irritation or rash occurs: Get medical advice/attention
IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing

Precautionary Statements - Storage
Store in accordance with local regulations

Precautionary Statements - Disposal
Dispose of contents/container to an approved waste disposal plant

2.3. Other Hazards Hazards not otherwise classified (HNOC)
Not Applicable

2.4 Other information

Not Applicable

3. Composition/Information on Ingredients

Substance
Mixture

Chemical Name	CAS-No	Weight %
Crystalline silica (Quartz) (Respirable)	14808-60-7	40 - 50%
PORTLAND CEMENT	65997-15-1	20 - 30%
CALCIUM OXIDE/LIME	1305-78-8	0 - 10%
Calcium carbonate (Limestone)	1317-65-3	0 - 10%
CALCIUM SULFATE HEMIHYDRATE	13397-24-5	0 - 10%
ASHES (RESIDUES)	68131-74-8	0 - 10%
CLAY (KAOLIN)	1332-58-7	0 - 10%

Aluminum Sulfate	10043-01-3	0 - 10%
ALUMINUM OXIDE	1344-28-1	0 - 10%
CALCIUM SULFATE	7778-18-9	0 - 10%
MAGNESIUM OXIDE	1309-48-4	0 - 10%
Calcium Metasilicate	13983-17-0	0 - 10%
2-Phenoxyethanol	122-99-6	0 - 10%
Iron oxide	1309-37-1	0 - 10%

The exact percentage (concentration) of composition has been withheld as a trade secret.

4. First aid measures

4.1 Description of first-aid measures

General advice If symptoms persist, call a physician.

Eye contact IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Call a physician if irritation develops or persists.

Skin contact Immediate medical attention is not required. Call a physician if irritation develops or persists.

Inhalation Immediate medical attention is not required. Get medical attention if symptoms occur. Call a physician if irritation develops or persists.

Ingestion If swallowed, do not induce vomiting - seek medical advice.

4.2 Most important symptoms and effects, both acute and delayed

Symptoms No information available.

4.3 Indication of any immediate medical attention and special treatment needed

Notes to physician No information available.

5. Fire-Fighting Measures

5.1 Extinguishing media

Suitable extinguishing media
Use extinguishing measures that are appropriate to local circumstances and the surrounding environment.

Unsuitable Extinguishing Media None.

5.2 Special hazards arising from the substance or mixture

Special Hazard
No information available.

Hazardous Combustion Products No information available.

Explosion Data
Sensitivity to Mechanical Impact No information available.
Sensitivity to Static Discharge No information available.

5.3 Advice for firefighters

As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

6. Accidental Release Measures

6.1 Personal precautions, protective equipment and emergency procedures

Personal protection needs must be evaluated based on information provided on this sheet and the special circumstances created by the spill including; the material spilled, the quantity of the spill, the area in which the spill occurred, and the training and the expertise of employees in the area responding to the spill.

6.2 Environmental precautions

Prevent product from entering drains. Do not flush into surface water or sanitary sewer system. See Section 12 for additional Ecological information.

6.3 Methods and materials for containment and cleaning up

Methods for Containment Spills and leaks are not likely. Prevent further leakage or spillage if safe to do so.

Methods for cleaning up Pick up and transfer to properly labeled containers.

7. Handling and storage

7.1 Precautions for safe handling

Advice on safe handling Handle in accordance with good industrial hygiene and safety practice.

Hygiene measures Handle in accordance with good industrial hygiene and safety practice.

7.2 Conditions for safe storage, including any incompatibilities

Storage Conditions Keep in a dry, cool and well-ventilated place. Keep out of the reach of children. Store in accordance with local regulations.

Materials to Avoid Strong oxidizing agents. Strong acids. Strong bases.

8. Exposure controls/personal protection

8.1 Exposure Guidelines

Chemical Name	ACGIH TLV	OSHA PEL	British Columbia	Alberta	Quebec	Ontario TWAEV
Crystalline silica (Quartz) (Respirable) 14808-60-7	TWA: 0.025 mg/m³ respirable fraction	: (30)/(%SiO2 + 2) mg/m³ TWA total dust : (250)/(%SiO2 + 5) mppcf TWA respirable fraction : (10)/(%SiO2 + 2) mg/m³ TWA respirable fraction	TWA: 0.025 mg/m³	TWA: 0.025 mg/m³	TWA: 0.1 mg/m³	TWA: 0.10 mg/m³
PORTLAND CEMENT 65997-15-1	TWA: 1 mg/m³ particulate matter containing no asbestos and <1% crystalline silica, respirable fraction	TWA: 15 mg/m³ total dust TWA: 5 mg/m³ respirable fraction TWA: 50 mppcf <1% Crystalline silica	TWA: 10 mg/m³ TWA: 3 mg/m³	TWA: 10 mg/m³	TWA: 10 mg/m³ TWA: 5 mg/m³	TWA: 1 mg/m³
CALCIUM OXIDE/LIME 1305-78-8	TWA: 2 mg/m³	TWA: 5 mg/m³	TWA: 2 mg/m³	TWA: 2 mg/m³	TWA: 2 mg/m³	TWA: 2 mg/m³
Calcium carbonate (Limestone) 1317-65-3	-	TWA: 15 mg/m³ total dust TWA: 5 mg/m³ respirable fraction	TWA: 10 mg/m³ TWA: 3 mg/m³ STEL: 20 mg/m³	TWA: 10 mg/m³	TWA: 10 mg/m³	
CALCIUM SULFATE HEMIHYDRATE 13397-24-5	TWA: 10 mg/m³ inhalable fraction	TWA: 15 mg/m³ total dust TWA: 5 mg/m³ respirable fraction	TWA: 10 mg/m³ TWA: 3 mg/m³ STEL: 20 mg/m³	TWA: 10 mg/m³	TWA: 10 mg/m³ TWA: 5 mg/m³	TWA: 10 mg/m³
ASHES (RESIDUES) 68131-74-8	TWA: 1 mg/m³ Cu dust and mist	-				
CLAY (KAOLIN)	TWA: 2 mg/m³	TWA: 15 mg/m³	TWA: 2 mg/m³	TWA: 2 mg/m³	TWA: 5 mg/m³	TWA: 2 mg/m³

1332-58-7	particulate matter containing no asbestos and <1% crystalline silica, respirable fraction	total dust TWA: 5 mg/m³ respirable fraction				
Aluminum Sulfate 10043-01-3	-	-		TWA: 2 mg/m³	TWA: 2 mg/m³	
ALUMINUM OXIDE 1344-28-1	TWA: 1 mg/m³ respirable fraction	TWA: 15 mg/m³ total dust TWA: 5 mg/m³ respirable fraction	TWA: 1.0 mg/m³	TWA: 10 mg/m³	TWA: 10 mg/m³	TWA: 1 mg/m³
CALCIUM SULFATE 7778-18-9	TWA: 10 mg/m³ inhalable fraction	TWA: 15 mg/m³ total dust TWA: 5 mg/m³ respirable fraction	TWA: 10 mg/m³	TWA: 10 mg/m³	TWA: 10 mg/m³ TWA: 5 mg/m³	TWA: 10 mg/m³
MAGNESIUM OXIDE 1309-48-4	TWA: 10 mg/m³ inhalable fraction	TWA: 15 mg/m³ fume, total particulate	TWA: 10 mg/m³ TWA: 3 mg/m³ STEL: 10 mg/m³	TWA: 10 mg/m³	TWA: 10 mg/m³	TWA: 10 mg/m³
Calcium Metasilicate 13983-17-0	-	-			TWA: 10 mg/m³ TWA: 5 mg/m³	
2-Phenoxyethanol 122-99-6	-	-				TWA: 25 ppm TWA: 141 mg/m³ Skin
Iron oxide 1309-37-1	TWA: 5 mg/m³ respirable fraction	TWA: 10 mg/m³ fume TWA: 15 mg/m³ total dust TWA: 5 mg/m³ respirable fraction	TWA: 10 mg/m³ TWA: 3 mg/m³ TWA: 5 mg/m³ STEL: 10 mg/m³	TWA: 5 mg/m³	TWA: 5 mg/m³ TWA: 10 mg/m³	TWA: 5 mg/m³

8.2 Appropriate engineering controls

Engineering Measures Ensure adequate ventilation, especially in confined areas.

8.3 Individual protection measures, such as personal protective equipment

Eye/Face Protection Safety glasses with side-shields.

Skin and body protection Wear protective gloves/ protective clothing.

Respiratory protection Effective dust mask. If exposure limits are exceeded or irritation is experienced, NIOSH/MSHA approved respiratory protection should be worn.

Hygiene measures See section 7 for more information

9. Physical and chemical properties

9.1 Information on basic physical and chemical properties

Physical state	Solid		
Appearance	Powder	**Color**	Off-white or Gray
Odor	No information available	**Odor Threshold**	No information available

Property	Values	Remarks • Methods
pH		
Melting/freezing point		No information available
Boiling point/boiling range		No information available
Flash Point		No information available
Evaporation rate		
Flammability (solid, gas)		No information available
Flammability Limits in Air		
upper flammability limit		No information available
lower flammability limit		No information available
Vapor pressure		No information available
Vapor density		No information available
Specific Gravity	1.60 - 2.80 g/cc	
Water solubility	Soluble in water	
Solubility in other solvents		No information available
Partition coefficient		No information available
Autoignition temperature		
Decomposition temperature		
Viscosity, kinematic		No information available
Viscosity, dynamic		No information available
Explosive properties		No information available
Oxidizing Properties		No information available

9.2 Other information

Volatile organic compounds (VOC) content	no data available
Density	14.0 - 23.0 lbs/gal

10. Stability and Reactivity

10.1 Reactivity

No dangerous reaction known under conditions of normal use

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10.2 Chemical stability

Stable under recommended storage conditions

10.3 Possibility of hazardous reactions

None under normal processing.

10.4 Conditions to Avoid

Do not freeze. To avoid thermal decomposition, do not overheat.

10.5 Incompatible Materials

Strong oxidizing agents. Strong acids. Strong bases.

10.6 Hazardous Decomposition Products

Thermal decomposition can lead to release of irritating gases and vapors.

11. Toxicological information

11.1 Acute toxicity

Numerical measures of toxicity: Product Information

The following values are calculated based on chapter 3.1 of the GHS document

Oral LD50 5,589.00 mg/kg

Numerical measures of toxicity: Component Information

Chemical Name	LD50 Oral	LD50 Dermal	LC50 Inhalation
Crystalline silica (Quartz) (Respirable) 14808-60-7	500 mg/kg (Rat)	-	-
CALCIUM OXIDE/LIME 1305-78-8	500 mg/kg (Rat)	-	-
ASHES (RESIDUES) 68131-74-8	2000 mg/kg (Rat)	-	-
Aluminum Sulfate 10043-01-3	1930 mg/kg (Rat)	-	-
ALUMINUM OXIDE 1344-28-1	5000 mg/kg (Rat)	-	-
CALCIUM SULFATE 7778-18-9	3000 mg/kg (Rat)	-	-
2-Phenoxyethanol 122-99-6	1260 mg/kg (Rat)	= 5 mL/kg (Rabbit)	-
Iron oxide 1309-37-1	10000 mg/kg (Rat)	-	-

11.2 Information on toxicological effects

Skin corrosion/irritation
Product Information
• Corrosive to skin. Contact with skin may cause irritation or severe burns and scarring.
Component Information
• No information available

Serious eye damage/eye irritation
Product Information
• Risk of serious damage to eyes
Component Information
• No information available

Respiratory or skin sensitization
Product Information
• May cause allergic skin reaction
Component Information
• No information available

Germ cell mutagenicity
Product Information
• No information available
Component Information
• No information available

Carcinogenicity
Product Information

• The table below indicates whether each agency has listed any ingredient as a carcinogen
Component Information
•

Chemical Name	ACGIH	IARC	NTP	OSHA
Crystalline silica (Quartz) (Respirable) 14808-60-7	A2	Group 1	Known	
ASHES (RESIDUES) 68131-74-8	-	Group 1	Known	

Reproductive toxicity
Product Information
• No information available
Component Information
• No information available

STOT - single exposure
No information available

STOT - repeated exposure

• May cause adverse liver effects

Other adverse effects
Product Information
• No information available
Component Information
• No information available

Aspiration hazard
Product Information
• No information available
Component Information
• No information available

12. Ecological information

12.1 Toxicity

Ecotoxicity No information available

Ecotoxicity effects

Chemical Name	Toxicity to algae	Toxicity to fish	Toxicity to daphnia and other aquatic invertebrates
CALCIUM OXIDE/LIME 1305-78-8	-	LC50: 96 h Cyprinus carpio 1070 mg/L static	-
CALCIUM SULFATE 7778-18-9	-	LC50: 96 h Lepomis macrochirus 2980 mg/L static LC50: 96 h Pimephales promelas 1970 mg/L static	-
2-Phenoxyethanol 122-99-6	EC50: 72 h Desmodesmus subspicatus 500 mg/L	LC50: 96 h Pimephales promelas 337 - 352 mg/L flow-through LC50: 96 h Pimephales promelas 366 mg/L static	EC50: 48 h Daphnia magna 500 mg/L

12.2 Persistence and degradability

No product level data available.

12.3 Bioaccumulative potential

Some components of this material have some potential to bioaccumulate but not all have been tested

Chemical Name	log Pow
2-Phenoxyethanol 122-99-6	1.13

12.4 Mobility in soil

No information available.

12.5 Other adverse effects

No information available

13. Disposal Considerations

13.1 Waste treatment methods

Dispose of in accordance with federal, state, and local regulations.

14. Transport Information

DOT Not regulated

MEX Not regulated

IMDG Not regulated

IATA Not regulated

15. Regulatory information

15.1 International Inventories

TSCA	-
DSL	-
EINECS/ELINCS	-
ENCS	-
IECSC	-
KECL	-
PICCS	-
AICS	-
NZIoC	-

TSCA - United States Toxic Substances Control Act Section 8(b) Inventory
DSL - Canadian Domestic Substances List
EINECS/ELINCS - European Inventory of Existing Chemical Substances/European List of Notified Chemical Substances
PICCS - Philippines Inventory of Chemicals and Chemical Substances
ENCS - Japan Existing and New Chemical Substances **IECSC**
- China Inventory of Existing Chemical Substances **KECL** -
Korean Existing and Evaluated Chemical Substances
PICCS - Philippines Inventory of Chemicals and Chemical Substances
AICS - Australian Inventory of Chemical Substances
NZIoC - New Zealand Inventory of Chemicals

15.2 U.S. Federal Regulations

SARA 313
Section 313 of Title III of the Superfund Amendments and Reauthorization Act of 1986 (SARA). This product contains a chemical or chemicals which are subject to the reporting requirements of the Act and Title 40 of the Code of Federal Regulations, Part 372:

Chemical Name	SARA 313 - Threshold Values %
ASHES (RESIDUES) 68131-74-8	1.0 0.1
ALUMINUM OXIDE 1344-28-1	1.0

15.3 Pesticide Information

Not applicable

15.4 U.S. State Regulations

California Proposition 65

This product contains the following Proposition 65 chemicals:

Chemical Name	California Prop. 65
Crystalline silica (Quartz) (Respirable) - 14808-60-7	Carcinogen
ASHES (RESIDUES) - 68131-74-8	Carcinogen
METHANOL - 67-56-1	Developmental
Acetaldehyde - 75-07-0	Carcinogen

16. Other information

NFPA	**Health Hazard** 2	**Flammability** 0	**Instability** 0	**Physical and chemical hazards** -
HMIS	**Health Hazard** 2	**Flammability** 0	**Physical Hazard** 0	**Personal protection** E

Legend:

ACGIH (American Conference of Governmental Industrial Hygienists)
Ceiling (C)
DOT (Department of Transportation)
EPA (Environmental Protection Agency)
IARC (International Agency for Research on Cancer)
International Air Transport Association (IATA)
International Maritime Dangerous Goods (IMDG)
NIOSH (National Institute for Occupational Safety and Health)
NTP (National Toxicology Program)
OSHA (Occupational Safety and Health Administration of the US Department of Labor)
PEL (Permissible Exposure Limit)
Reportable Quantity (RQ)
Skin designation (S*)
STEL (Short Term Exposure Limit)
TLV® (Threshold Limit Value)
TWA (time-weighted average)

Revision Date 22-Mar-2017

Revision Note

No information available

Disclaimer

The information provided on this SDS is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guide for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered as a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other material or in any process, unless specified in the text.

End of Safety Data Sheet

B: Test Standards

B.1 ASTM E 96-00: Standard Test Methods for Water Vapor Transmission of Materials

Designation: E 96 – 00

Standard Test Methods for Water Vapor Transmission of Materials[1]

This standard is issued under the fixed designation E 96; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 These test methods cover the determination of water vapor transmission (WVT) of materials through which the passage of water vapor may be of importance, such as paper, plastic films, other sheet materials, fiberboards, gypsum and plaster products, wood products, and plastics. The test methods are limited to specimens not over 1¼ in. (32 mm) in thickness except as provided in Section 9. Two basic methods, the Desiccant Method and the Water Method, are provided for the measurement of permeance, and two variations include service conditions with one side wetted and service conditions with low humidity on one side and high humidity on the other. Agreement should not be expected between results obtained by different methods. That method should be selected which more nearly approaches the conditions of use.

1.2 The values stated in inch-pound units are to be regarded as the standard. Metric inch-pound conversion factors for WVT, permeance, and permeability are stated in Table 1. All conversions of mm Hg to Pa are made at a temperature of 0°C.

1.3 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 168 Terminology Relating to Thermal Insulating Materials[2]

D 449 Specification for Asphalt Used in Dampproofing and Waterproofing[3]

D 2301 Specification for Vinyl Chloride Plastic Pressure-Sensitive Electrical Insulating Tape[4]

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[5]

TABLE 1 Metric Units and Conversion Factors[A,B]

Multiply	by	To Obtain (for the same test condition)
	WVT	
g/h·m²	1.43	grains/h·ft²
grains/h·ft²	0.697	g/h·m²
	Permeance	
g/Pa·s·m²	1.75×10^{7}	1 Perm (inch-pound)
1 Perm (inch-pound)	5.72×10^{-8}	g/Pa·s·m²
	Permeability	
g/Pa·s·m	6.88×10^{8}	1 Perm inch
1 Perm inch	1.45×10^{-9}	g/Pa·s·m

[A] These units are used in the construction trade. Other units may be used in other standards.
[B] All conversions of mm Hg to Pa are made at a temperature of 0°C.

3. Terminology

3.1 Definitions of terms used in this standard will be found in Terminology C 168, from which the following is quoted:

"*water vapor permeability*—the time rate of water vapor transmission through unit area of flat material of unit thickness induced by unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions.

3.1.1 *Discussion*—Permeability is a property of a material, but the permeability of a body that performs like a material may be used. Permeability is the arithmetic product of permeance and thickness.

"*water vapor permeance*—the time rate of water vapor transmission through unit area of flat material or construction induced by unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions.

3.1.2 *Discussion*—Permeance is a performance evaluation and not a property of a material.

3.2 *water vapor transmission rate*—the steady water vapor flow in unit time through unit area of a body, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface."

4. Summary of Test Methods

4.1 In the Desiccant Method the test specimen is sealed to the open mouth of a test dish containing a desiccant, and the assembly placed in a controlled atmosphere. Periodic weighings determine the rate of water vapor movement through the specimen into the desiccant.

4.2 In the Water Method, the dish contains distilled water, and the weighings determine the rate of vapor movement

[1] These test methods are under the jurisdiction of ASTM Committee C-16 on Thermal Insulation and are the direct responsibility of Subcommittee C16.33 on Thermal Insulation Finishes and Vapor Transmission.

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[2] *Annual Book of ASTM Standards*, Vol 04.06.

[3] *Annual Book of ASTM Standards*, Vol 04.04.

[4] *Annual Book of ASTM Standards*, Vol 10.01.

[5] *Annual Book of ASTM Standards*, Vol 14.02.

through the specimen from the water to the controlled atmosphere. The vapor pressure difference is nominally the same in both methods except in the variation, with extremes of humidity on opposite sides.

5. Significance and Use

5.1 The purpose of these tests is to obtain, by means of simple apparatus, reliable values of water vapor transfer through permeable and semipermeable materials, expressed in suitable units. These values are for use in design, manufacture, and marketing. A permeance value obtained under one set of test conditions may not indicate the value under a different set of conditions. For this reason, the test conditions should be selected that most closely approach the conditions of use. While any set of conditions may be used and those conditions reported, standard conditions that have been useful are shown in Appendix X1.

6. Apparatus

6.1 *Test Dish*—The test dish shall be of any noncorroding material, impermeable to water or water vapor. It may be of any shape. Light weight is desirable. A large, shallow dish is preferred, but its size and weight are limited when an analytical balance is chosen to detect small weight changes. The mouth of the dish shall be as large as practical and at least 4.65 in.^{2}(3000 mm^{2}x). The desiccant or water area shall be not less than the mouth area except if a grid is used, as provided in 12.1, its effective area shall not exceed 10 % of the mouth area. An external flange or ledge around the mouth, to which the specimen may be attached, is useful when shrinking or warping occurs. When the specimen area is larger than the mouth area, this overlay upon the ledge is a source of error, particularly for thick specimens. This overlay material should be masked as described in 10.1 so that the mouth area defines the test area. The overlay material results in a positive error, indicating excessive water vapor transmission. The magnitude of the error is a complex function of the thickness, ledge width, mouth area, and possibly the permeability. This error is discussed by Joy and Wilson.[6] This type of error should be limited to about 10 to 12 %. For a thick specimen the ledge should not exceed ¾ in. (19 mm) for a 10-in. (254-mm) or larger mouth (square or circular) or ⅛in. (3 mm) for a 5-in. (127-mm) mouth (square or circular). For a 3-in. (76-mm) mouth (square or circular) the ledge should not exceed 0.11 in. (2.8 mm) wide. An allowable ledge may be interpolated for intermediate sizes or calculated according to Joy and Wilson.[6] A rim around the ledge (Fig. X1.1) may be useful. If a rim is provided, it shall be not more than ¼in. (6 mm) higher than the specimen as attached. Different depths may be used for the Desiccant Method and Water Method, but a ¾-in. (19-mm) depth (below the mouth) is satisfactory for either method.

6.2 *Test Chamber*—The room or cabinet where the assembled test dishes are to be placed shall have a controlled temperature and relative humidity. The temperature chosen shall be between 21 and 32°C (70 and 90°F), and shall be maintained constant within ±1°C (± 2°F). A temperature of 32°C (90°F) is recommended (Note 1). The relative humidity shall be maintained at 50 ± 2 %, (When extremes of humidities are desired, the temperature shall be 38 ± 1°C (100 ± 1.8°F) The relative humidity shall be 90 ± 2 %. Both temperature and relative humidity shall be measured frequently[7], or preferably recorded continuously. Air shall be continuously circulated throughout the chamber, with a velocity sufficient to maintain uniform conditions at all test locations. The air velocity over the specimen shall be between 0.02 and 0.3 m-s^{-1}(0.066 and 1ft/s). Suitable racks shall be provided on which to place the test dishes within the test chamber.

NOTE 1—Simple temperature control by heating alone is usually made possible at 32°C (90°F). However, it is very desirable to enter the controlled space, and a comfortable temperature is more satisfactory for that arrangement. Temperatures of 23°C (73.4°F) and 26.7°C (80°F) are in use and are satisfactory for this purpose. With cyclic control, the average test temperature may be obtained from a sensitive thermometer in a mass of dry sand. The temperature of the chamber walls facing a specimen over water should not be cooler than the water to avoid condensation on the test specimen.

6.3 *Balance and Weights*—The balance shall be sensitive to a change smaller than 1 % of the weight change during the period when a steady state is considered to exist. The weights used shall be accurate to 1 % of the weight change during the steady-state period. For example: -perm (5.7×10^{-11}kg·Pa^{-1}·s^{-1}·m^{-2}) specimen 10 in. (254 mm) square at 80°F (26.7°C) passes 8.6 grains or 0.56 g/day. In 18 days of steady state, the transfer is 10 g. For this usage, the balance must have a sensitivity of 1 % of 10 g or 0.1 g and the weights must be accurate to 0.1 g. If, however, the balance has a sensitivity of 0.2 g or the weights are no better than 0.2 g, the requirements of this paragraph can be met by continuing the steady state for 36 days. An analytical balance that is much more sensitive will permit more rapid results on specimens below 1 perm (5.7×10^{-11}kg·Pa^{-1}·s^{-1}·m^{-2}) when the assembled dish is not excessively heavy. A light wire sling may be substituted for the usual pan to accommodate a larger and heavier load.

7. Materials

7.1 *Desiccant and Water*:

7.1.1 For the Desiccant Method, anhydrous calcium chloride in the form of small lumps that will pass a No. 8 (2.36-mm) sieve, and free of fines that will pass a No. 30 (600-µm) sieve, shall be used (Note 2). It shall be dried at 400°F (200°C) before use.

NOTE 2—If $CaCl_2$ will react chemically on the specimen, an adsorbing desiccant such as silica gel, activated at 400°F (200°C), may be used; but the moisture gain by this desiccant during the test must be limited to 4 %.

7.1.2 For the Water Method, distilled water shall be used in the test dish.

7.2 *Sealant*—The sealant used for attaching the specimen to the dish, in order to be suitable for this purpose, must be highly

[6] Joy, F. A., and Wilson, H. G., "Standardization of the Dish Method for Measuring Water Vapor Transmissions," National Research Council of Canada, Research Paper 279, January 1966, p. 263.

[7] The minimum acceptable is to preform this measurement each time the sample is weighed.

resistant to the passage of water vapor (and water). It must not lose weight to, or gain weight from, the atmosphere in an amount, over the required period of time, that would affect the test result by more than 2 %. It must not affect the vapor pressure in a water-filled dish. Molten asphalt or wax is required for permeance tests below 4 perms (2.3×10^{-10} kg·Pa^{-1}·s^{-1}·m^{-2}). Sealing methods are discussed in Appendix X2.

8. Sampling

8.1 The material shall be sampled in accordance with standard methods of sampling applicable to the material under test. The sample shall be of uniform thickness. If the material is of nonsymmetrical construction, the two faces shall be designated by distinguishing marks (for example, on a one-side-coated sample, "I" for the coated side and "II" for the uncoated side).

9. Test Specimens

9.1 Test specimens shall be representative of the material tested. When a product is designed for use in only one position, three specimens shall be tested by the same method with the vapor flow in the designated direction. When the sides of a product are indistinguishable, three specimens shall be tested by the same method. When the sides of a product are different and either side may face the vapor source, four specimens shall be tested by the same method, two being tested with the vapor flow in each direction and so reported.

9.2 A slab, produced and used as a laminate (such as a foamed plastic with natural "skins") may be tested in the thickness of use. Alternatively, it may be sliced into two or more sheets, each being separately tested and so reported as provided in 9.4, provided also, that the "overlay upon the cup ledge" (6.1) of any laminate shall not exceed ⅛ in. (3 mm).

9.3 When the material as used has a pitted or textured surface, the tested thickness shall be that of use. When it is homogeneous, however, a thinner slice of the slab may be tested as provided in 9.4.

9.4 In either case (9.2 or 9.3), the tested overall thickness, if less than that of use, shall be at least five times the sum of the maximum pit depths in both its faces, and its tested permeance shall be not greater than 5 perms (3.3 metric perms).

9.5 The overall thickness of each specimen shall be measured at the center of each quadrant and the results averaged. Measurement of specimens of 0.125 in. or less in thickness shall be made to the nearest 0.0001 in. Measurement of specimens greater than 0.125 in. in thickness shall be made to the nearest 0.001 in.

9.6 When testing any material with a permeance less than 0.05 perms or when testing a low permeance material that may be expected to lose or gain weight throughout the test (because of evaporation or oxidation), it is strongly recommended that an additional specimen, or "dummy," be tested exactly like the others, except that no desiccant or water is put in the dish. Failure to use this dummy specimen to establish modified dish weights may significantly increase the time required to complete the test. Because time to reach equilibrium of water permeance increases as the square of thickness, thick, particularly hygroscopic, materials may take as long as 60 days to reach equilibrium conditions.

10. Attachment of Specimen to Test Dish

10.1 Attach the specimen to the dish by sealing (and clamping if desired) in such a manner that the dish mouth defines the area of the specimen exposed to the vapor pressure in the dish. If necessary, mask the specimen top surface, exposed to conditioned air so that its exposure duplicates the mouth shape and size and is directly above it. A template is recommended for locating the mask. Thoroughly seal the edges of the specimen to prevent the passage of vapor into, or out of, or around the specimen edges or any portion thereof. The same assurance must apply to any part of the specimen faces outside their defined areas. Suggested methods of attachment are described in Appendix X2.

NOTE 3—In order to minimize the risk of condensation on the interior surface of the sample when it is placed in the chamber, the temperature of the water prior to preparation of the test specimen should be within ±2°F (±1.1°C) of the test condition.

11. Procedure for Desiccant Method

11.1 Fill the test dish with desiccant within ¼ in. (6 mm) of the specimen. Leave enough space so that shaking of the dish, which must be done at each weighing, will mix the desiccant.

11.2 Attach the specimen to the dish (see 10.1) and place it in the controlled chamber, specimen up, weighing it at once. (This weight may be helpful to an understanding of the initial moisture in the specimen.)

11.3 Weigh the dish assembly periodically, often enough to provide eight or ten data points during the test. A data point is the weight at a particular time. The time that the weight is made should be recorded to a precision of approximately 1 % of the time span between successive weighing. Thus, if weighings are made every hour, record the time to the nearest 30 s; if recordings are made every day, a time to the nearest 15 min would be allowed. At first the weight may change rapidly; later a steady state will be reached where the rate of change is substantially constant. Weighings should be accomplished without removal of the test dishes from the controlled atmosphere, but if removal is prescribed necessary, the time the specimens are kept at different conditions, temperature or relative humidity, or both, should be kept to a minimum. When results of water vapor transmission are expected to be less than .05 perm, a dummy specimen is strongly recommended. Such a dummy specimen should be attached to an empty cup in the normal manner. The environmental effects of temperature variation and buoyancy variability due to barometric pressure fluctuation can be arithmetically tared out of the weighing values. This precaution permits earlier and more reliable achievement of equilibrium conditions. Analyze the results as prescribed in 13.1.

11.4 Terminate the test or change the desiccant before the water added to the desiccant exceeds 10 % of its starting weight (Note 1 and Note 3). This limit cannot be exactly determined and judgement is required. The desiccant gain may be more or less than the dish weight-gain when the moisture content of the specimen has changed.

NOTE 4—The WVT of some materials (especially wood) may depend on the ambient relative humidity immediately before the test. An apparent

hysteresis results in higher WVT if the prior relative humidity was above the test condition and vice versa. It is therefore recommended that specimens of wood and paper products be conditioned to constant weight in a 50 % relative humidity atmosphere before they are tested. Some specimens may be advantageously preconditioned to minimize the moisture that the specimen will give up to the desiccant. This applies when the specimen is likely to have high moisture content or when it is coated on the top (vapor source) side.

12. Procedure for Water Method

12.1 Fill the test dish with distilled water to a level ¾ ± ¼ in. (19 ± 6 mm) from the specimen. The air space thus allowed has a small vapor resistance, but it is necessary in order to reduce the risk of water touching the specimen when the dish is handled. Such contact invalidates a test on some materials such as paper, wood, or other hygroscopic materials. The water depth shall be not less than ⅛ in. (3 mm) to ensure coverage of the dish bottom throughout the test. However, if the dish is of glass, its bottom must be visibly covered at all times but no specific depth is required. Water surges may be reduced in placing a grid of light noncorroding material in the dish to break the water surface. This grid shall be at least ¼ in. (6 mm) below the specimen, and it shall not reduce the water surface by more than 10 % (Note 4).

NOTE 5—For the Water Method, baking the empty dish and promptly coating its mouth with sealant before assembly is recommended. The water may be added most conveniently after the specimen is attached, through a small sealable hole in the dish above the water line.

12.2 Attach the specimen to the dish (see 10.1). Some specimens are likely to warp and break the seal during the test. The risk is reduced by preconditioning the specimen, and by clamping it to the dish ledge (if one is provided).

12.3 Weigh the dish assembly and place it in the controlled chamber on a true horizontal surface. Follow the procedure given in 11.3. If the test specimen cannot tolerate condensation on the surface, the dish assembly shall not be exposed to a temperature that differs by more than 5°F (2.8°C) from the control atmosphere to minimize the risk of condensation on the specimen. When results of water vapor transmission are expected to be less than .05 perm, a dummy specimen is strongly recommended. Such a dummy specimen should be attached to an empty cup in the normal manner. The environment effects of temperature variation and buoyancy variability due to barometric pressure fluctuation can be arithmetically tared out of the weighing values. This precaution permits earlier and more reliable achievement of equilibrium conditions. Analyze the results as prescribed in 13.1.

12.4 Where water is expected to be in contact with the barrier in service, proceed as in 11.3 except place the dish in an inverted position. The dish must be sufficiently level so that water covers the inner surface of the specimen despite any distortion of the specimen due to the weight of the water. With highly permeable specimens it is especially important to locate the test dish so that air circulates over the exposed surface at the specified velocity. The test dishes may be placed on the balance in the upright position for weighing, but the period during which the wetted surface of the specimen is not covered with water must be kept to a minimum.

13. Calculation and Analysis of Results

13.1 The results of the rate of water vapor transmission may be determined either graphically or numerically.

13.1.1 *Dummy Specimen*—If a dummy specimen has been used to compensate for variability in test conditions, due to temperature or barometric pressure, or both, the daily recorded weights can be adjusted by calculating the weight change from initial to time of weighing. This adjustment is made by reversing the direction of the dummy's weight change, relative to its initial weight, and modifying all the appropriate specimen weight(s) recorded at this time. This permits earlier achievement of equilibrium conditions. An alternate procedure, particulary for tests of long duration and more than six weighings, is to subtract the arithmetic mean slope of the rate of weight change of the dummy specimen from the arithmetic mean slope of each similar specimen to get an effective rate of weight change. These procedures are also desirable if the specimen is changing weight due to a curing process while under test.

13.1.2 *Graphic Analysis*—Plot the weight, modified by the dummy specimen when used, against elapsed time, and inscribe a curve which tends to become straight. Judgment here is required and numerous points are helpful. When a straight line adequately fits the plot of at least six properly spaced points (periodic weight changes matching, or exceeding 20 % of the multiple of 100 times the scale sensitivity), a nominally steady state is assumed, and the slope of the straight line is the rate of water vapor transmission.

13.1.3 *Numerical Analysis*—A mathematical least squares regression analysis of the weight, modified by the dummy specimen when used, as a function of time will give the rate of water vapor transmission. An uncertainty, or standard deviation of this rate, can also be calculated to define the confidence band. For very low permeability materials, this method can be used to determine the results after 30 to 60 days when using an analytical balance, with a sensitivity of ±1 mg, even if the weight change does not meet the 100 times the sensitivity requirement of 6.3. Specimens analyzed in this manner must be clearly identified in the report.

13.2 Calculate the water vapor transmission, WVT, and permeance as follows:

13.2.1 *Water Vapor Transmission*:

$$WVT = G/tA = (G/t)/A \quad (1)$$

where:

In inch-pound units:

G = weight change, grains (from the straight line),
t = time during which G occurred, h,
G/t = slope of the straight line, grains/h,
A = test area (cup mouth area), ft^2, and
WVT = rate of water vapor transmission, grains/h·ft^2.

In metric units:

G = weight change (from the straight line), g,
t = time, h,
G/t = slope of the straight line, g/h,
A = test area (cup mouth area), m^2, and
WVT = rate of water vapor transmission, g/h·m^2.

13.2.2 *Permeance*:

$$\text{Permeance} = WVT/\Delta p = WVT/S(R_1 - R_2) \quad (2)$$

where:
In inch-pound units:
Δp = vapor pressure difference, in. Hg,
S = saturation vapor pressure at test temperature, in. Hg,
R_1 = relative humidity at the source expressed as a fraction (the test chamber for desiccant method; in the dish for water method), and
R_2 = relative humidity at the vapor sink expressed as a fraction

In metric units:
Δp = vapor pressure difference, mm Hg (1.333×10^2 Pa),
S = saturation vapor pressure at test temperature, mm Hg (1.333×10^2 Pa),
R_1 = relative humidity at the source expressed as a fraction (the test chamber for desiccant method; in the dish for water method), and
R_2 = relative humidity at the vapor sink expressed as a fraction.

13.2.3 In the controlled chamber the relative humidity and temperature are the average values actually measured during the test and (unless continuously recorded) these measurements shall be made as frequently as the weight measurements. In the dish the relative humidity is nominally 0 % for the desiccant and 100 % for the water. These values are usually within 3 % relative humidity of the actual relative humidity for specimens below 4 perms (2.3×10^{-7} g·Pa^{-1}·s^{-1}·m^{-2}) when the required conditions are maintained (no more than 10 % moisture in $CaCl_2$ and no more than 1 in. (25 mm) air space above water).

13.3 Only when the test specimen is homogeneous (not laminated) and not less than ½in. (12.5 mm) thick, calculate its average permeability (perm in.) (metric perm-cm) as follows:

$$\text{Average permeability} = \text{permeance} \times \text{thickness} \quad (3)$$

NOTE 6—*Example*: In a desiccant test that ran 288 h (12 days) on an exposed area of 100 in.^{2} (0.0645 m^2), it was found that the rate of gain was substantially constant after 48 h and during the subsequent 240 h, the weight gain was 12 g. The controlled chamber conditions were measured at 89.0°F (31.7°C) and 49 % relative humidity.

Required: WVT and permeance
Calculation (inch-pound units):
G/t = 12 g × $^{15.43\ grains}/_{g}$ ÷ 240 h
= 0.771 grains/h,
A = 100 in.^{2} × $^{1\ ft^2}/_{144\ in.^2}$ = 0.695 ft^2,
S = 1.378 in. Hg (from standard references tables),
R_1 = 49 % (in chamber),
R_2 = 0 % (vapor sink), and
WVT = 0.771 grains/h ÷ 0.694 ft^2 = 1.11 grains/ft^2·h.
Permeance = WVT/ΔP = WVT/S ($R_1 - R_2$)
= 1.11 grains/ft^2·h ÷ 1.378 in. Hg (0.49 – 0)
= 1.64 grains/ft^2·h·in. Hg = 1.64 perms

Calculation (metric units):
G/t = 12 g/240 h = 0.05 g/h,
A = 0.0645 m^2,
S = 35 mm Hg (from reference tables),
= 35 mm Hg × 1.333×10^2 Pa/mm Hg = 46.66×10^2 Pa,
R_1 = 49 % (in chamber),
R_2 = 0 % (vapor sink), and
WVT = 0.05 g/h ÷ 0.0645 m^2 = 0.775 g/h·m^2.
Permeance = WVT/ΔP – WVT/S ($R_1 - R_2$)
= 0.775 g/h·m^2 × 1 h/3600s ÷ 46.66×10^2 Pa × (0.49 – 0)
= 9.42×10^{-8} g/Pa·s·m^2

13.4 Metric units and conversion factor are given in Table 1.

14. Report

14.1 The report shall include the following:

14.1.1 Identification of the material tested, including its thickness.

14.1.2 Test method used (desiccant or water).

14.1.3 Test temperature.

14.1.4 Relative humidity in the test chamber.

14.1.5 Permeance of each specimen in perms (to two significant figures).

14.1.6 The side of each specimen on which the higher vapor pressure was applied. (The sides shall be distinguished as "side A" and "side B" when there is no obvious difference between them. When there is an obvious difference, this difference shall also be stated, such as "side A waxed" and "side B unwaxed.").

14.1.7 The average permeance of all specimens tested in each position.

14.1.8 The permeability of each specimen (as limited by 13.3), and the average permeability of all specimens tested.

14.1.9 Include a portion of the plot indicating the section of the curve used to calculate permeability.

14.1.10 State design of cup and type or composition of sealant.

15. Precision and Bias [8]

15.1 *Precision*—Table 2 is based on an interlaboratory tests conducted in 1988 and 1991.[8, 9] In 1988 four materials (A, B, C, D) were tested using the dessicant method and the water method in triplicate. Fifteen laboratories contributed data, with full results secured from four laboratories. In 1991 ten laboratories contributed data for material E, using triplicate specimens, again using both the dessicant method and the water method.

15.1.1 Test results were analyzed using Practice E 691.

15.2 *Bias*—This test method has no bias because water vapor transmission of materials is defined in terms of this test method.

16. Keywords

16.1 permeability; plastics (general); plastic sheet and film; sheet material; thermal-insulating materials; thermal insulation permeability films; water vapor transmission (WVT)

[8] Supporting data have been filed at ASTM Headquarters. Request RR: C-16-1014.
[9] Available from E. I. DuPont de Nemours & Co., Inc., Polymer Products Dept., Wilmington, DE 19898.

TABLE 2 Precision Results from Interlaboratory Testing

For Desiccant Method at 73.4°F.								
Material	Thickness, in.	WVT (mean), perm	Repeatability[A]			Reproducibility[A]		
			S	*CV*%	*LSD*	*S*	*CV*%	*LSD*
A	0.001	0.606	0.0166	2.70	0.047	0.098	15.0	0.278
B	0.0055	0.0129	0.0028	22.1	0.008	0.0055	42.6	0.016
C	0.5	0.0613	0.0044	7.22	0.012	0.0185	30.6	0.052
D	1.0	0.783	0.0259	3.30	0.073	0.0613	7.8	0.174
E	0.014	0.0461	0.0023	4.99	0.007	0.0054	11.7	0.015
For Water Method at 73.4°F.								
Material	Thickness, in.	WVT (mean), perm	Repeatability[A]			Reproducibility[A]		
			S	*CV*%	*LSD*	*S*	*CV*%	*LSD*
A	0.001	0.715	0.0134	1.95	0.039	0.156	21.9	0.44
B	0.0055	0.0157	0.0022	13.8	0.0062	0.0021	19.4	0.006
C	0.5	0.097	0.0055	5.7	0.016	0.0195	20.9	0.055
D	1.0	1.04	0.0192	1.8	0.054	0.217	20.9	0.62
E	0.014	0.0594	0.0034	5.7	0.010	0.0082	13.8	0.023

[A]For this data,

S = standard deviation,
CV = percent coefficient of variation ($S \times 100$/mean), and
LSD = least significant difference between two individual test results based on a 95 % confidence level = $2\sqrt{2}S$.

[B]Material B was Teflon® PTFE fluorocarbon resin brand of tetrafluoroethylene. It was extremely difficult to provide a seal to this sample, which accounts for the poor repeatability.

APPENDIX

(Nonmandatory Information)

X1. STANDARD TEST CONDITIONS

X1.1 Standard test conditons that have been useful are:

X1.1.1 *Procedure A*—Desiccant Method at 73.4°F (23°C).

X1.1.2 *Procedure B*—Water Method at 73.4°F (23°C).

X1.1.3 *Procedure BW*—Inverted Water Method at 73.4°F (23°C).

X1.1.4 *Procedure C*—Desiccant Method at 90°F (32.2°C).

X1.1.5 *Procedure D*—Water Method at 90°F (32.2°C).

X1.1.6 *Procedure E*—Desiccant Method at 100°F (37.8°C).

X2. CUP DESIGN AND SEALING METHODS

X1.2 An ideal sealing material has the following properties:

X1.2.1 Impermeability to water in either vapor or liquid form.

X1.2.2 No gain or loss of weight from or to the test chamber (evaporation, oxidation, hygroscopicity, and water solubility being undersirable).

X1.2.3 Good adhesion to any specimen and to the dish (even when wet).

X1.2.4 Complete conformity to a rough surface.

X1.2.5 Compatibility with the specimen and no excessive penetration into it.

X1.2.6 Strength or pliability (or both).

X1.2.7 Easy handleability (including desirable viscosity and thermal of molten sealant).

X1.2.8 Satisfactory sealants possess these properties in varying degrees and the choice is a compromise, with more tolerance in items at the beginning of this list for the sake of those at the latter part of the list when the requirements of 7.2 are met (Note A2). Molten asphalt or wax is required for permeance tests below 4 perms (2.6 metric perms). Tests to determine sealant behavior should include:

X1.2.8.1 An impervious specimen (metal) normally sealed to the dish and so tested, and

X1.2.8.2 The seal normally assembled to an empty dish with no specimen and so tested.

X1.3 The following materials are recommended for general use when the test specimen will not be affected by the temperature of the sealant:

X1.3.1 Asphalt, 180 to 200°F (82 to 93°C) softening point, meeting the requirements of Specification D 449, Type C. Apply by pouring.

X1.3.2 Beeswax and rosin (equal weights). A temperature of 275°F (135°C) is desirable for brush application. Pour at lower temperature.

X1.3.3 Microcrystalline wax[10] (60 %), mixed with refined crystalline paraffin wax (40 %).

X1.4 The materials listed in X1.4.1 are recommended for particular uses such as those shown in Fig. X1.1. The suggested procedure described in X1.4.2 applies to an 11-⅜-in. (289-mm) square specimen if its permeance exceeds 4 perms (2.6 metric perms) (limited by evaporation of sealants).

X1.4.1 *Materials*:

X1.4.1.1 Aluminum foil, 0.005 in. (0.125 mm) minimum thickness.

X1.4.1.2 Tape, meeting the requirements of Specification D 2301, vinyl chloride plastic pressure-sensitive, electrical insulating tape.

X1.4.1.3 Cement, contact bond, preferably rubber base.

X1.4.2 *Procedure*:

X1.4.2.1 *Step 1*—Seal aluminum foil around edges of specimen, leaving a 100-in.^{2}(0.0654-m^2) exposed test area on each side. Use contact bond cement as directed by the manufacturer.

X1.4.2.2 *Step 2*—Spread sealant on inside of rim and ledge. Place desiccant (dry), or water and surge control material (wet) in pan. Press specimen in place. Avoid squeezing compound into the test area.

X1.4.2.3 *Step 3*—Coat outside of rim and bottom of ledge with contact bond cement, and place foil strips from edge of template, around rim, and bottom of ledge.

X1.5 A method of using hot asphalt, as applied to a 10-in. (254-mm) square-mouth dish with ledge and rim, is as follows:

X1.5.1 *Apparatus*:

X1.5.1.1 *Template*—A square frame of brass or steel, 1/16 in. (5 mm) thick and ¾ in. (19 mm) deep. The 3/16-in. (5-mm) thickness is tapered to zero at the bottom of the frame where it will touch the test specimen and maintain a 10-in. (254-mm) square test area.

[10] Grade Nos. 2305 or 2310 of the Mobil Oil Corp., or their equivalent, have been found satisfactory for this purpose.

X1.5.1.2 *Sealant*—Asphalt (see X1.3.1 used at the proper pouring consistency of 375 to 450°F (179 to 232°C).

X1.5.1.3 *Melting Pot* for the asphalt, electrically heated, with one dimension greater than 11⅜ in. (289 mm).

X1.5.1.4 *Small Ladle* for pouring.

X1.5.2 *Procedure*—Mark the 11⅜-in. (289-mm) square specimen with a line at an equal distance from each edge, so that the area enclosed by the lines is as nearly as possible a 10-in. (254-mm) square. The template may be used for marking. Dip each edge of the specimen in molten asphalt up to the line, so that the test area is defined and all edges are coated with a heavy layer of asphalt. Place the specimen over the pan containing water or desiccant. Lightly oil the template or coat with petroleum jelly on its outer side, and place on the specimen. Pour molten asphalt into the space between the template and the rim of the pan. After the asphalt has cooled for a few minutes, the template should be easily removable.

X1.6 Hot wax may be applied like asphalt. It may also be applied (freely) with a small brush. Its lower working temperature may be advantageous when a specimen contains moisture.

X1.7 Several designs for dishes with supporting rings and flanges are shown in Fig. X1.2. Various modifications of these designs may be made provided that the principle of prevention of edge leakage by means of a complete seal is retained. The dishes may be constructed of any rigid, impermeable, corrosion-resistant material, provided that they can be accommodated on the available analytical balance. A lightweight metal, such as aluminum or one of its alloys, is generally used for larger-size dishes. In some cases when an aluminum dish is employed and moisture is allowed to condense on its surface, there may be appreciable oxidation of the aluminum with a resulting gain in weight. Any gain in weight will ordinarily depend on the previous history of the dish and the cleanness of the surface. An empty dish carried through the test procedure as a control will help to determine whether any error may be expected from this cause. When aluminum dishes are used for the water methods, a pressure may develop inside the assembly

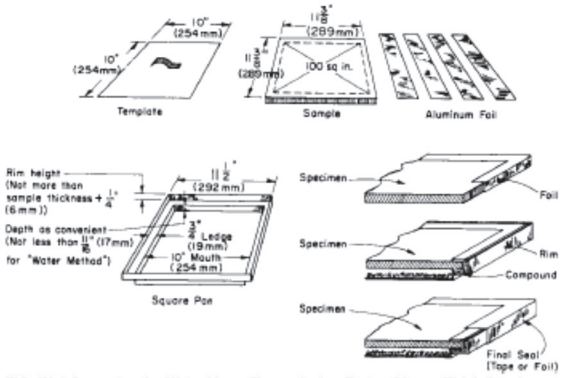

FIG. X1.1 Apparatus for Water Vapor Transmission Tests of Large Thick Specimens

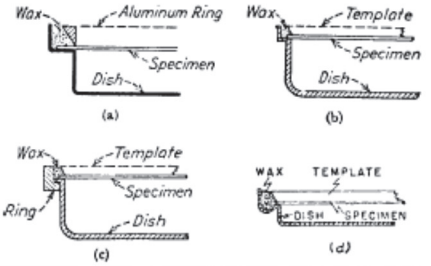

FIG. X1.2 Several Types of Dishes for Water Vapor Transmission Tests of Materials in Sheet Form

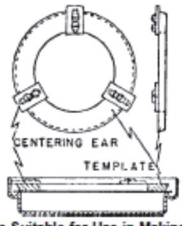

FIG. X1.3 Template Suitable for Use in Making the Wax Seals on Test Dishes

during a test due to corrosion. This can cause seal failure or otherwise affect the result. Where this is a problem, it can be overcome by providing inside the dish a protective coating of baked-on epoxy resin or similar material. Dishes with flanges or rings that project from the inner walls of the dish are to be avoided, as such projections influence the diffusion of the water vapor. The depth of the dish for the water procedures is such that there is a 0.80 ± 0.20 in. (20 ± 5-mm) distance between the water surface and the under surface of the specimen, with a water depth of about 0.20 in. (5 mm).

X1.7.1 For the desiccant-in-dish procedures, the dishes need not be as deep as those required for the water-in-dish procedures. The desiccant is within ¼ in. (6 mm) of the under surface, and a minimum depth of only ½ in. (12 mm) of desiccant is required.

X1.7.2 The dishes shown in Fig. X1.2 require a molten seal.

X1.7.3 A template such as is shown in Fig. X1.3 is usually used for defining the test area and effecting the wax seal. It consists of a circular metal dish ⅛in. (3.18 mm) or more in thickness with the edge beveled to an angle of about 45°. The diameter of the bottom (smaller) face of the template is approximately equal to, but not greater than, the diameter of the effective opening of the dish in contact with the specimen. Small guides may be attached to the template to center it automatically on the test specimen. A small hole through the template to admit air, and petrolatum applied to the beveled edge of the template facilitate its removal after sealing the test specimen to the dish. In use, the template is placed over the test specimen and when it is carefully centered with the dish opening, molten wax is flowed into the annular space surrounding the beveled edge of the template. As soon as the wax has solidified, the template is removed from the sheet with a twisting motion. The outside flange of the dish should be high enough to extend over the top of the specimen, thus allowing the wax to completely envelop the edge.

X1.7.4 Gasketed types of seals are also in use on appropriately designed dishes. These simplify the mounting of the specimen, but must be used with caution, since the possibility of edge leakage is greater with gasketed seals than with wax seals. Gasketed seals are not permitted for the measurement of permeance less than 44 perms (2.3×10^{-7} g·Pa^{-1}·s^{-1}·m^{2}). As a further precaution when gasketed seals are used instead of preferred sealants, a blank test run is suggested using glass or metal as a dummy specimen.

X1.7.5 A suitable weighing cover consists of a circular disk of aluminum 1/32 to 3/32 in. (0.8 to 2.4 mm) in thickness provided with a suitable knob in the center for lifting. The cover fits over the test specimen when assembled and makes contact with the inside beveled surface of the wax seal at, or just above, the plane of the specimen. The cover is free of sharp edges which might remove the wax and is numbered or otherwise identified to facilitate its exclusive use with the same dish.

NORDTEST Method

NT BUILD 499
Approved 2002-05

1(4)

UDC 620.179.13:691.21

CLADDING PANELS: TEST FOR BOWING

Key words: Cladding panels, bowing, test method

1 SCOPE

This Nordtest method describes a laboratory procedure for determining the bowing potential of natural stone panels intended for building facades. The method shall therefore be used to select natural stone types that are fit for cladding purposes, without demonstrating this phenomenon.

2 FIELD OF APPLICATION

The method is used for indicating thermal and moisture induced bowing of various natural building stones, especially carbonate rocks such as marble and limestone.

3 REFERENCES

1. Schouenborg, B., Grelk, B., Brundin, J-A. & Alnæs, L. SP RAPPORT 2000: 28 Nordtest project 1443-99: Buktningsprovning av marmor för fasadbeklädnad (Bow test for facade panels of marble).
2. prEN 12670 – *"Terminology of Natural Stone"*.
3. prEN 12440 – *"Denomination of Natural Stone"*.
4. NT BUILD 500 (Field method for measurement of bowing of cladding panels).

4 DEFINITIONS

Bowing: In this test method, bowing is used as a term for a slab that has changed from an original flat and plane shape to a curved or dished shape in a concave or convex direction. Other terms commonly used for the same phenomenon are warping and dishing.

Concave: Centre part of the specimen is bowing upwards, away from the moist substratum. Compare NT BUILD 500 where the centre part of the panel is facing inwards (to the facade).

Convex: Centre part of the specimen is bowing towards the moist substratum.

Object testing: Testing of panels taken directly from the production of cladding elements or from buildings.

5 SAMPLING

The method of sampling shall be stated in the test report and shall be chosen so that the samples are representative of the batch to be tested. For material characterisation purposes samples shall be selected from three perpendicular orientations (e.g. parallel, normal and perpendicular to foliation). For "object testing" it is sufficient to test one set of samples with the same orientation as the slabs to be used on the facade.

One test set consists of five specimens of size 400 mm by 100 mm, thickness as in use. For material characterisation the specimens shall have a thickness of 30 mm. The specimens shall be randomly chosen for the tests. At least one side of the samples (the side exposed to moisture) shall be smooth but not polished.

6 TEST METHOD

6.1 Principle

Bowing is measured on test samples exposed to moisture from one side and infrared heating on the other side. The temperature interval is from 20 to 80°C, one cycle each 24 hours.

The moisture gradient is produced by letting the samples rest on an approx. 5 mm thick wet heat stable filter cloth or a 5–10 mm thin bed of sand that gradually dries under the influence of the infrared heater. The temperature of the sand is not controlled by other means than the temperature of the laboratory, i.e. 20 ± 2°C.

6.2 Equipment

- A suitably sized, non-corrosive container for water immersion of the specimens.
- A thermometer at least ranging from 15 to 85°C, with a tolerance of ±2°C.
- A watch or a timer.
- A container to moisten the specimens on one side and to expose them to heating on the other side (see example in Figures 1 and 2).

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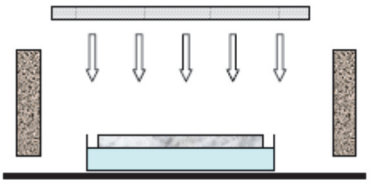


Figure 1. Schematic sketch of an insulated container for testing the potential bowing properties of natural stone. The test specimens are placed in a pan, on top of a filter cloth (needle felt) or a sand bed. The heat is distributed from above. The walls are preferably insulated.

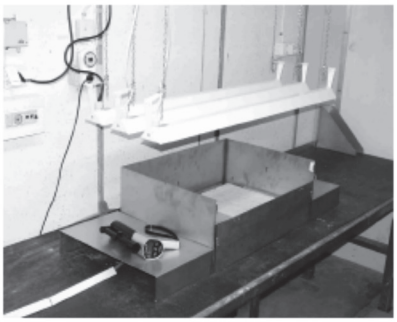


Figure 2 A. Test container with infrared heating lamps above.

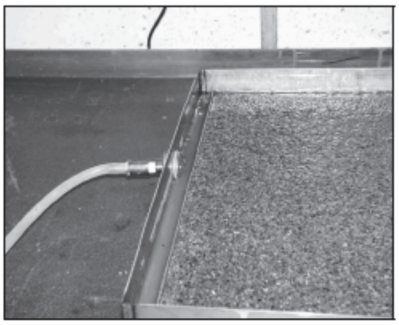


Figure 2 B. Inner pan with sand bed and a water hose. Here complemented with an adjustable water level outlet.

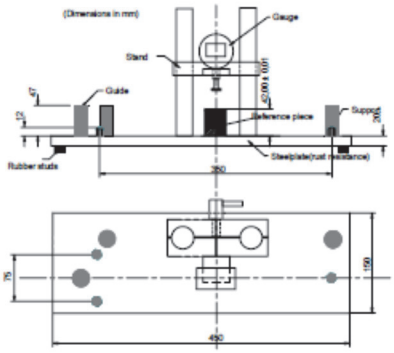


Figure 3. Schematic drawing of a bow-test rig.

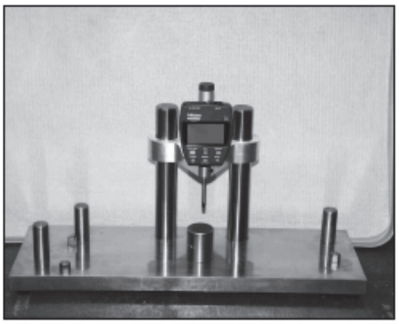


Figure 4. Example of a bow-test rig with a digital gauge and a reference cylinder for zero setting. The reference piece (a cylinder) is preferably made of invar steel and has a height of 30 mm, i.e. the same as the thickness of the specimens.

- Heat stable filter cloth (needle felt) or sand to place the specimens on in the above container. No specification for the sand other than a capillary suction greater than the thickness of the sand bed.
- Radiant heating devices, capable of keeping the specimen's surface at 80°C.
- A "bow-test rig" for measuring the amount of bow (see example in Figure 3 and 4). The dial/digital gauge for measuring the amount of bow shall be readable to thousands of one mm. It shall have an accuracy better than ±0,01 mm.
- A thermometer capable of measuring the surface temperature of the specimens.

6.3 Pre-conditioning of test samples

All loose material shall be washed from the surface of the specimens using tap water.

Dry the specimens in 40ºC for one week. Some marble types are sensitive for higher temperature. Changes of the stone properties shall not be included during the pre-conditioning.

After drying, cool the specimens to room temperature 20ºC ± 2ºC. Each specimen is then labelled with a durable marking.

Each specimen is placed in an open container, partly immersed in distilled or filtered water to a depth of 10 mm ± 2 mm below the top of the specimen. The specimens are placed in the container at a distance of minimum 5 mm from each other and the distance to the sides of the container shall be at least 10 mm. Alternatively, the specimens may be placed in a single container provided that there is a minimum of 10 mm between the specimen and the sides of the container. The specimens shall be kept in the container for 24 hours at a water temperature of 20 ± 2ºC.

6.4 Test procedure and data processing

Before the specimens are exposed to temperature cycling, the difference in height between the top surface in the middle of the specimen (h) (see Figure 3) and the reference cylinder is measured with an accuracy of ±0.01 mm.

The container with the specimens is placed in an open insulated box under a group of radiant-heating devices (see example in Figure 2 A). The heaters are placed approximately 0.5 m above the specimens. A temperature-measuring sensor is placed on the top surface of one of the specimens. The heaters shall be arranged or adjusted by a regulator to provide a maximum surface temperature of 80ºC ± 2ºC on top of the specimens at the hottest stage of the temperature cycling. Check that the heat is evenly distributed by placing the temperature sensor on different places in the container.

The increase in the surface temperature of the specimens from 20ºC ± 2ºC to 80ºC ± 2ºC shall take place in not less than 1 hour and not more than 3 hours. The maximum temperature shall be maintained for 3 hours (Figure 5). The heater is then switched off, and the specimens are left in the container for at least 16 hours to cool down to ambient temperature (20ºC ± 2ºC).

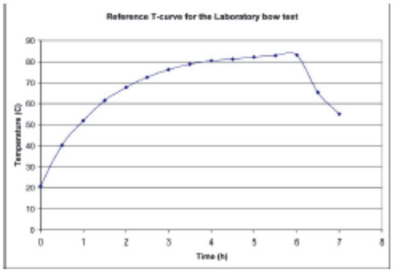


Figure 5. The preferred temperature cycle, measured on the surface of the specimens.

Before each temperature cycle (2 ± ½ hours), it is necessary to remoisten the specimens by filling the container with distilled or filtered water in such a way that the specimens once again are partly immersed in water to a depth of 10 mm ± 2 mm below the top of the specimens.

After each temperature cycle (approx. 22–24 hours) the change in height (h) of each specimen is measured at a temperature of 20ºC ± 2 ºC. After the 10^{th} cycle, measure the change in height every second cycle.

At least 40 cycles shall be carried out. After the last temperature cycle the height (h) is determined on both sides of the specimens to ensure that the result does not represent an increase in volume due to immersion in water but pure bowing. Any such volumetric expansion shall be subtracted from the final bow result.

The magnitude of bowing is calculated as the difference between the first gauge reading and the final reading divided by 350 mm, i.e. the length between the supports under the specimens.

$\tau = \Delta h/L$ (length) mm/m

Δh: Change in height in mm (after 40 cycles)
L: Length between the supports (0.35 m).

6.5 Applicability

The validation of the test method relies on the fact that stone types that show bowing damage on building facades also bow in this test. Stone types that are known to not have produced bowing on facades (e.g. granite) do not bow in the test.

6.6 Uncertainty

The precision data presented are preliminary and have been obtained within an earlier Nordtest project, in which some varying procedures have been used.

r_1 is here calculated as 2,78 times the pooled standard deviation (s_1) of 3 marble types and one limestone. The test on each stone type was performed on 4–6 test specimens. s_1 was determined to 0,025 and r_1 to 0,07 mm.

6.7 Test report

The test report shall include the following information (when relevant)

a) Name and address of the testing laboratory

b) Identification number of the test report

c) Name and address of the organisation or the person who ordered the test

d) Purpose of the test

e) Method of sampling and other circumstances (date and person responsible for sampling)
f) Name and address of the manufacturer or the supplier of the tested object
g) Name and other identification marks of the test specimens
h) Description of the test specimens
i) Date of supply of the test specimens
j) Date of test.
k) Test method
l) Condition of the test specimens (i.e. orientation of stone fabric in relation to the test object and the applied force), environmental data during the test if relevant (temperature, RH etc.)
m) Any deviations from the test method
n) Test results (in SI units), see section 6.4
o) Statement about the uncertainty of the test results
p) Date and signature.

Designation: C880/C880M – 15

Standard Test Method for Flexural Strength of Dimension Stone[1]

This standard is issued under the fixed designation C880/C880M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the procedure for determining the flexural strength of stone by use of a simple beam using quarter-point loading.

1.2 Stone tests shall be made when pertinent for the situation when the load is perpendicular to the bedding plane and when the load is parallel to the bedding plane.

1.3 As required, the flexural tests shall also be conducted under wet conditions.

1.4 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E4 Practices for Force Verification of Testing Machines
C119 Terminology Relating to Dimension Stone
C1799 Guide to Dimension Stone Test Specimen Sampling and Preparation

3. Terminology

3.1 *Definitions*—All definitions are in accordance with Terminology C119.

4. Significance and Use

4.1 This test method is useful in indicating the differences in flexural strength between the various dimension stones. This test method also provides one element in comparing stones of the same type.

5. Apparatus

5.1 *Testing Machine* (Fig. 1), conforming to the requirements of the applicable sections of Practices E4. The quarter-point loading method shall be used in making flexure tests of stone employing bearing blocks which will ensure that forces applied to the beam will be vertical only and applied without eccentricity. The apparatus should be capable of maintaining the span length and distances between load-applying blocks and support blocks constant within ±0.05 in. [±1 mm]. The load should be capable of being applied at a uniform rate and in such a manner as to avoid shock.

6. Sampling

6.1 Select the sample to represent a true average of the type or grade of stone under consideration and of the quality supplied to the market under the type designation to be tested. The sample may be selected by the purchaser or his authorized representative from the quarried stone or taken from the natural ledge and shall be of adequate size to permit the preparation of the desired number of test specimens. When perceptible variations occur, the purchaser may select as many samples as are necessary for determining the variations in flexural strength.

NOTE 1—Refer to Guide C1799 for additional information on selecting, preparing, and conditioning test specimens.

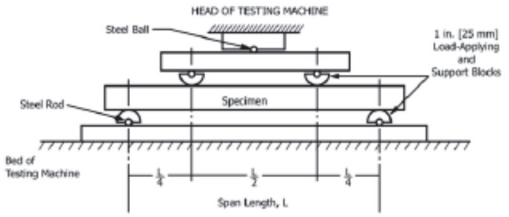
7. Test Specimen

7.1 The test specimens shall measure 4 in. [100 mm] wide by 1.25 in. [30 mm] thick by 15 in. [350 mm] long, with a span as tested of 12.5 in. [300 mm]. The sides of the specimen shall be at right angles with the top and bottom. The specimens shall have a fine abrasive finish on the planes perpendicular to the load and a fine saw finish on the other four planes. The dimensions of the specimen shall be measured and recorded to the nearest 0.01 in. [0.1 mm]. A minimum of five specimens shall be tested for each condition of test. The average value of the test results is reported as the flexural strength of the stone.

[1] This test method is under the jurisdiction of ASTM Committee C18 on Dimension Stone and is the direct responsibility of Subcommittee C18.01 on Test Methods.

Current edition approved May 1, 2015. Published July 2015. Originally approved in 1978. Last previous edition approved in 2009 as C880–09. DOI: 10.1520/C0880_C0880M-15.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.



NOTE 1—Apparatus may be used inverted.

FIG. 1 Diagrammatic View of a Suitable Apparatus for Flexure Test of Stone

7.2 Where this test method is specified in the physical requirements of an ASTM C18 Standard Specification for a dimension stone, the test specimens shall meet the requirements under 7.1.

7.3 Where the job thickness has been set (for example, the thickness of the stone panels for the project has been established), it is often requested to perform flexure tests at the job thickness. The following shall govern the specimen size where it is requested to test at the job thickness and the job thickness is other than 1.25 in. [30 mm]. The span as tested shall be 10 times the thickness. The specimen lengths shall be not less than 2 in. [50 mm] and not more than 4 in. [100 mm] greater than the span as tested. Where the thickness is less than 2.67 in. [70 mm], the width of the specimen shall be 4 in. [100 mm]. Where the thickness is greater than 2.67 in. [70 mm] the width shall be 1.5 times the thickness. Where the thickness is other than 1.25 in. [30 mm] and the specimen size is in accordance with the job thickness criteria noted in the foregoing, the average value of the test results shall be reported as the flexural strength of the stone at the job thickness. All other requirements shall be in accordance with 7.1.

7.4 Where the job surface finish has been set (for example, the architectural finish on the panels for the project has been established), it is often requested to perform flexure tests on specimens with the finish the same as on the job. The following shall govern when it is requested to test at the job surface finish. The specimens shall have a finish on one plane perpendicular to the load in accordance with the finish specified for the job. Unless there is data to the contrary, the positioning of the specimen should be with the finished face in flexural tension. The average value of the test results shall be reported as the flexural strength of the stone at the job surface finish. All other requirements shall be in accordance with 7.1 and 7.3.

7.5 Where the specimens conform to the requirements of 7.3 and 7.4, the average value of the test results shall be reported as the flexural strength of the stone at the job thickness and surface finish.

7.6 Test results obtained by this test method are those of flexural strength properties. In specific applications, test specimens of different geometry may give useful results in terms of a modulus of rupture value.

8. Conditioning

8.1 Before testing the specimens in a dry condition, dry them for 48 h at 140 ± 4°F [60 ± 2°C]. At the 46th, 47th and 48th hour, weigh the specimens to ensure that the weight is the same. If the weight continues to drop, continue to dry the specimens until there are three successive hourly readings with the same weight. After removing the specimens from the oven, cool them to room temperature in a desiccator before testing them.

8.2 Before testing the specimens in a wet condition, immerse them in water for 48 h at 72 ± 4°F [22 ± 2°C]. Test them immediately upon removal from the bath, wiping the specimens free of surface water.

9. Procedure

9.1 Assemble the apparatus and place the specimen on the span supports and adjust the quarter point loading blocks into contact with the specimen.

9.2 Apply the load at a uniform stress rate of 600 psi/min [4 MPa] to failure.

10. Calculation

10.1 Calculate the flexural strength, σ as follows:

$$\sigma = \frac{3WL}{4bd^2} \quad (1)$$

where:

σ = flexural strength, psi [MPa],
W = maximum load, lbf [N],
L = span, in. [mm],
L = 10 d,
b = width of specimen, in. [mm], $b \geq 1.5d$, and
d = depth of specimen, in. [mm].

11. Report

11.1 The report shall include the following:
11.1.1 Stone type.
11.1.2 Sizes of the specimens used.
11.1.3 Preconditioning procedure used.
11.1.4 Individual test results for each specimen.
11.1.5 Average value of the test results for each group using the following relation:

$$\bar{\sigma} = \frac{\text{sum of observed values}}{\text{number of tests}}$$

11.1.6 Standard deviation, s, of the test results for each group using the following relation:

$$s = \sqrt{\frac{\text{sum of (observed value} - \bar{\sigma})^2}{\text{number of tests} - 1}}$$

11.1.7 Any variations from the above procedural techniques.

11.2 The following additional information shall also be reported: identification of the sample, including name and location of the quarry, name and position of the ledge, date when sample was taken, and trade name or grade of the slate.

12. Precision and Bias

12.1 Individual variations in a natural product may result in deviation from accepted values. A precision section will be added when sufficient data are available to indicate acceptable tolerances in repeatability and reproducibility.

13. Keywords

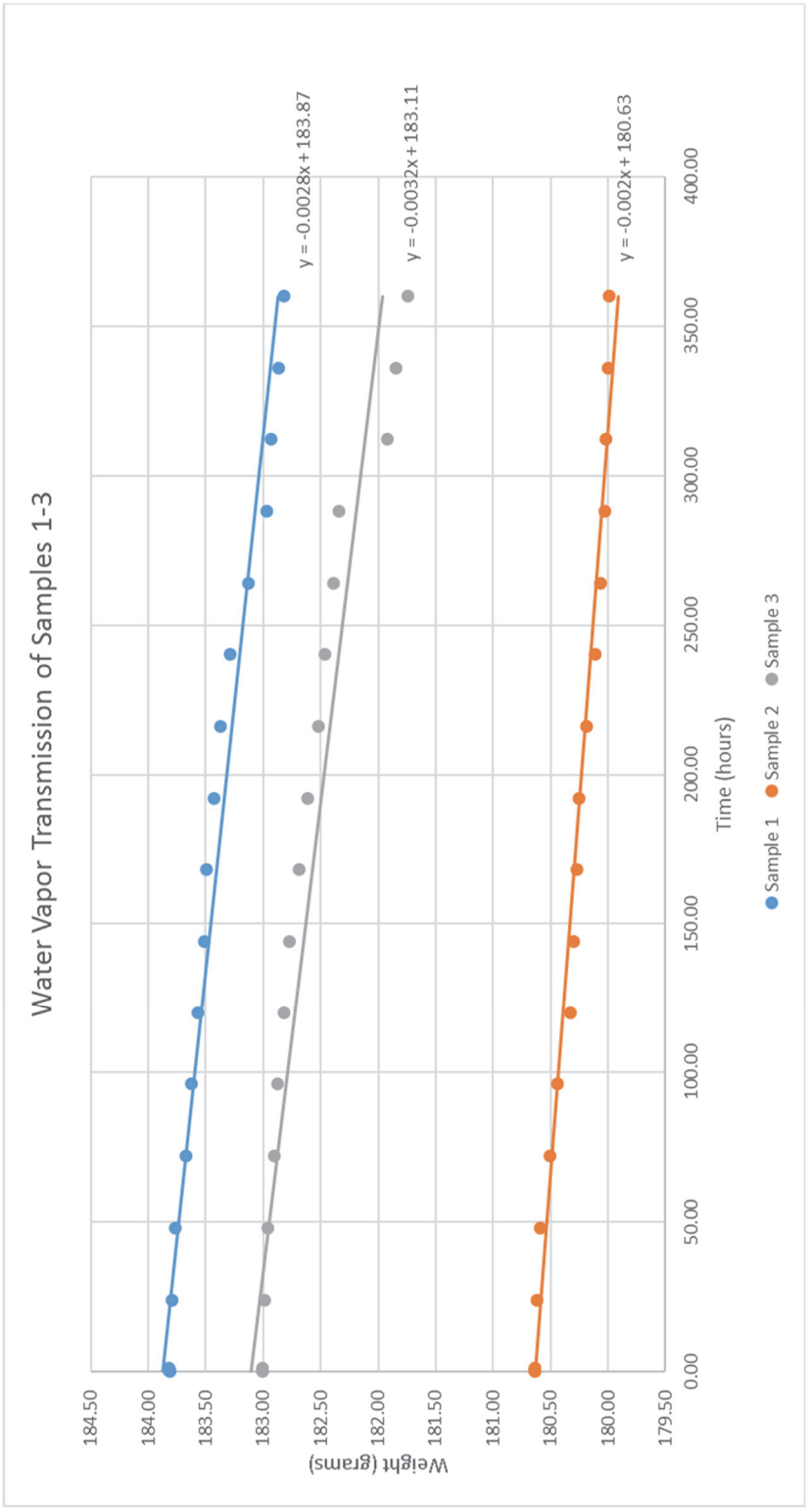
13.1 dimension stone; flexural strength; flexure; stone; test

C: Water Vapor Transmission Test Results

	Sample 1	Sample 2	Sample 3
M(d) (grams)	101.51	98.24	99.00
M(b) (grams)	10.06	10.12	10.29
M(bw) (grams)	182.12	177.60	180.30
M(a) (grams)	183.81	180.63	183.01

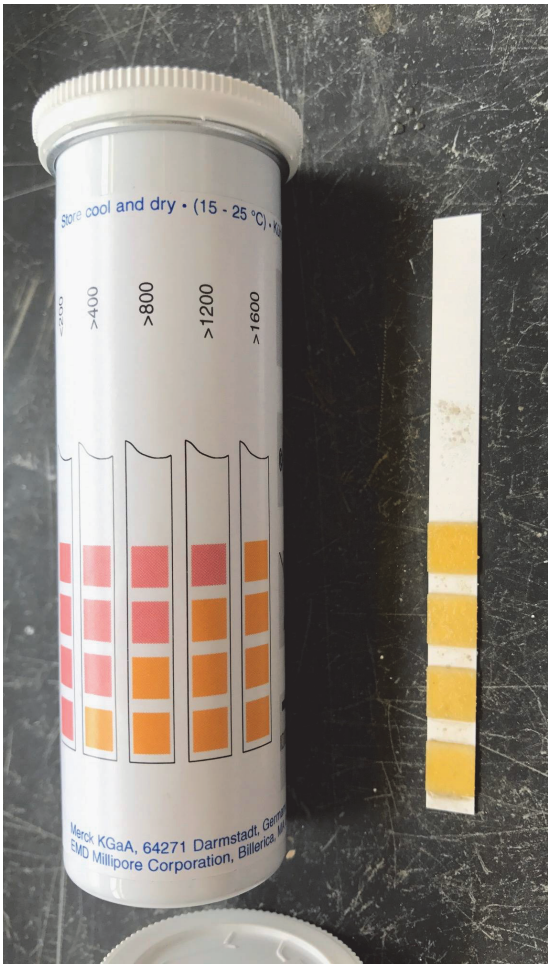
Time (hours)	M(n) (grams)	M(n) (grams)	M(n) (grams)
0.08	183.81	180.64	183.01
0.25	183.81	180.64	183.01
0.50	183.82	180.64	183.01
1.00	183.82	180.64	183.01
24.00	183.79	180.62	182.99
48.00	183.77	180.59	182.96
72.00	183.67	180.51	182.90
96.00	183.63	180.44	182.88
120.00	183.57	180.33	182.82
144.00	183.51	180.30	182.77
168.00	183.49	180.27	182.69
192.00	183.43	180.25	182.61
216.00	183.37	180.19	182.52
240.00	183.29	180.11	182.46
264.00	183.13	180.07	182.39
288.00	182.97	180.03	182.34
312.00	182.93	180.02	181.92
336.00	182.87	180.00	181.85
360.00	182.82	179.99	181.74

Standard Deviation of M(n) – M(a): 0.258 g

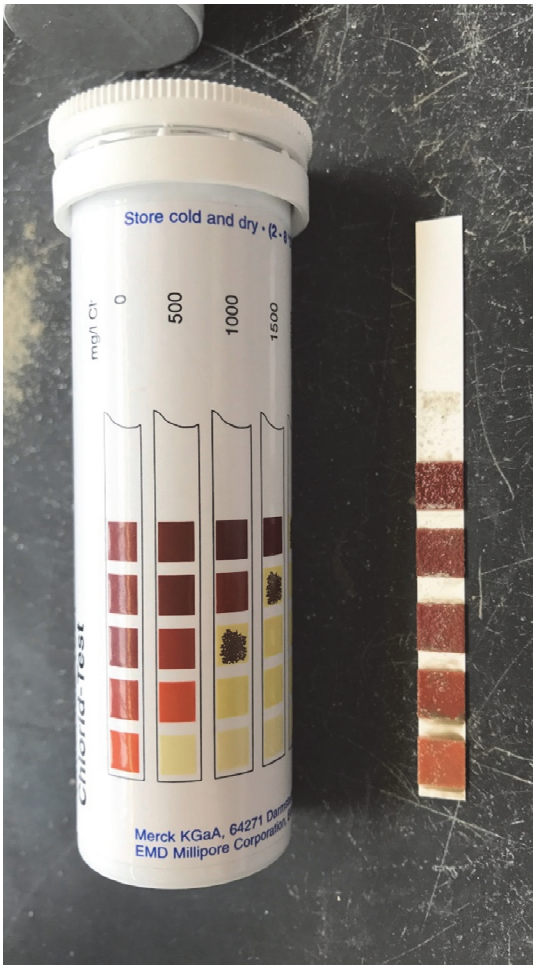

Water Vapor Transmission of Samples 1-3
y = -0.0028x + 183.87
y = -0.0032x + 183.11
y = -0.002x + 180.63
Weight (grams)
184.50
184.00
183.50
183.00
182.50
182.00
181.50
181.00
180.50
180.00
179.50
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
Time (hours)
Sample 1
Sample 2
Sample 3

D: Soluble Salt Content Test Results

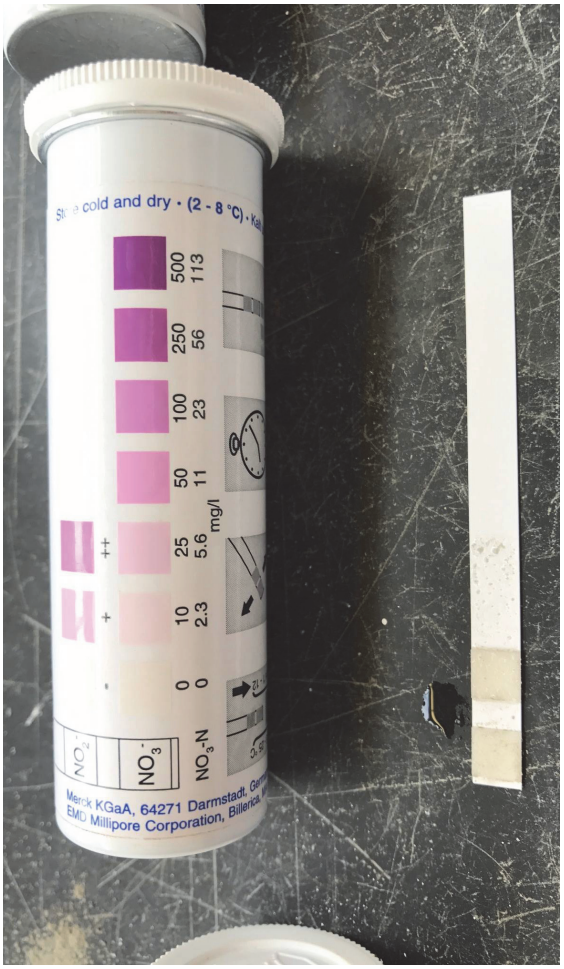
Sulfates



Chlorides



Nitrates


cold and dry • (2 - 8 °C)
500
113
250
56
100
23
50
11
25
5.6
mg/l
++
+
10
2.3
0
0
NO_3-N
NO_3^-
NO_2^-
Merck KGaA, 64271 Darmstadt, Ge
EMD Millipore Corporation, Billerica

E: Bowing Potential Test Results

Bow Meter Gauge Readings (1 = 0.002 mm)

	1	2	3	4	5	6	7	8	9	10
C1	0	97	123	140	148	42	81	86	81	134
A1	1982	2055	2176	2263	2229	2210	2272	2279	2272	2333
A2	3065	3075	3112	3195	3174	3199	3232	3112	3265	3304
A3	2310	2392	2434	2470	2598	2651	2613	2512	2566	2560
A4	2377	2443	2544	2656	2666	2693	2700	2699	2614	2732
A5	2001	2030	2097	2118	2238	2216	2289	2279	2331	2309
	11	12	13	14	15	16	17	18	19	20
C1	188	192	164	191	187	132	165	111	190	194
A1	2364	2365	2378	2399	2403	2373	2458	2455	2436	2482
A2	3282	3274	3299	3288	3328	3324	3322	3380	3406	3430
A3	2526	2582	2613	2632	2540	2592	2699	2639	2664	2598
A4	2714	2765	2786	2774	2765	2703	2766	2869	2868	2791
A5	2322	2398	2426	2415	2431	2401	2503	2531	2499	2507
	21	22	23	24	25	26	27	28	29	30
C1	285	236	245	277	269	242	236	202	185	177
A1	2481	2431	2487	2430	2474	2527	2533	2471	2503	2507
A2	3391	3396	3485	3409	3422	3414	3398	3234	3266	3397
A3	2612	2585	2572	2583	2632	2673	2545	2323	2534	2691
A4	2758	2705	2783	2823	2845	2868	2667	2503	2624	2714
A5	2455	2484	2495	2500	2532	2535	2488	2315	2455	2522
	31	32	33	34	35	36	37	38	39	40
C1	128	101	102	102	102	102	102	102	102	102
A1	2521	2490	2513	2524	2533	2539	2544	2557	2594	2626
A2	3368	3285	3255	3393	3358	3331	3324	3364	3472	3414
A3	2557	2406	2428	2487	2501	2482	2496	2505	2515	2595
A4	2745	2739	2766	2795	2806	2769	2758	2726	2718	2615
A5	2516	2510	2574	2583	2582	2589	2594	2613	2628	2622

	1	2	3	4	5	6	7	8	9	10
C2	0	129	135	139	265	231	295	322	365	276
CFR1	2701	2868	2912	2933	2838	2762	2741	2727	2713	2709
CFR2	2833	2803	2874	2882	2860	2805	2714	2808	2796	2762
	11	12	13	14	15	16	17	18	19	20
C2	350	277	286	250	206	245	308	245	201	224
CFR1	2745	2870	2795	2788	2632	2612	2595	2624	2622	2598
CFR2	2769	2728	2765	2758	2681	2711	2741	2699	2596	2626

Bowing Magnitude (mm/m)

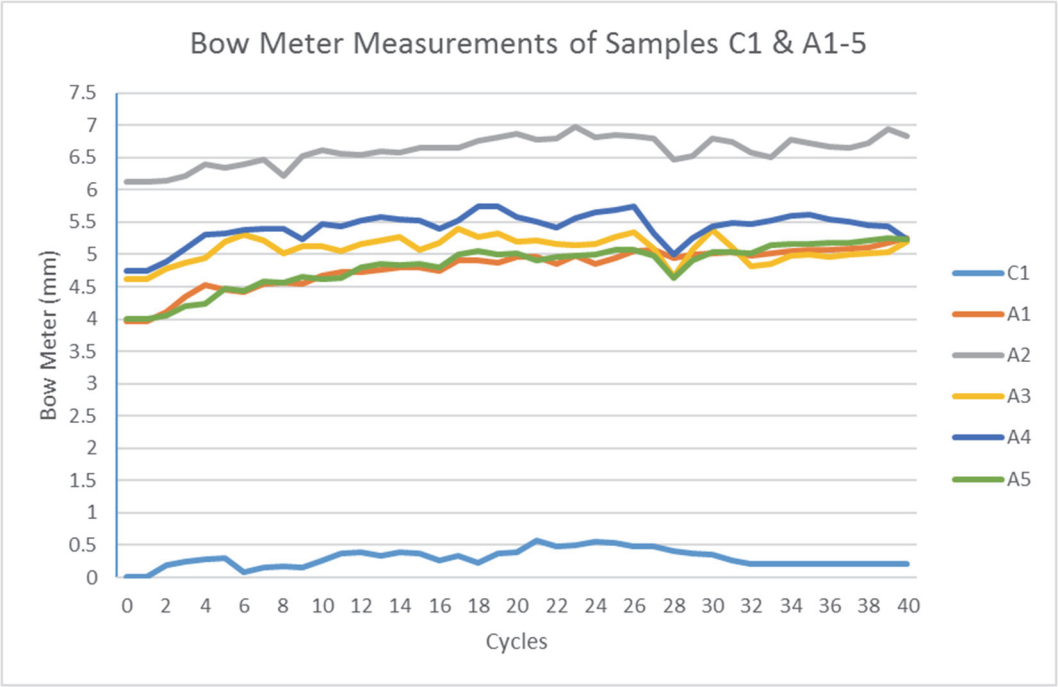
	1	2	3	4	5	6	7	8	9	10
C1	0.00	0.85	1.08	1.22	1.29	0.37	0.71	0.75	0.71	1.17
A1	0.00	0.64	1.70	2.46	2.16	1.99	2.54	2.60	2.54	3.07
A2	0.00	0.09	0.41	1.14	0.95	1.17	1.46	0.41	1.75	2.09
A3	0.00	0.72	1.08	1.40	2.52	2.98	2.65	1.77	2.24	2.19
A4	0.00	0.58	1.46	2.44	2.53	2.76	2.83	2.82	2.07	3.11
A5	0.00	0.25	0.84	1.02	2.07	1.88	2.52	2.43	2.89	2.69
	11	12	13	14	15	16	17	18	19	20
C1	1.64	1.68	1.43	1.67	1.64	1.15	1.44	0.97	1.66	1.70
A1	3.34	3.35	3.46	3.65	3.68	3.42	4.16	4.14	3.97	4.37
A2	1.90	1.83	2.05	1.95	2.30	2.27	2.25	2.76	2.98	3.19
A3	1.89	2.38	2.65	2.82	2.01	2.47	3.40	2.88	3.10	2.52
A4	2.95	3.39	3.58	3.47	3.39	2.85	3.40	4.30	4.30	3.62
A5	2.81	3.47	3.72	3.62	3.76	3.50	4.39	4.64	4.36	4.43
	21	22	23	24	25	26	27	28	29	30
C1	2.49	2.06	2.14	2.42	2.35	2.12	2.06	1.77	1.62	1.55
A1	4.37	3.93	4.42	3.92	4.30	4.77	4.82	4.28	4.56	4.59
A2	2.85	2.90	3.67	3.01	3.12	3.05	2.91	1.48	1.76	2.90
A3	2.64	2.41	2.29	2.39	2.82	3.18	2.06	0.11	1.96	3.33
A4	3.33	2.87	3.55	3.90	4.09	4.30	2.54	1.10	2.16	2.95
A5	3.97	4.23	4.32	4.37	4.65	4.67	4.26	2.75	3.97	4.56
	31	32	33	34	35	36	37	38	39	40
C1	1.12	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
A1	4.72	4.44	4.65	4.74	4.82	4.87	4.92	5.03	5.35	5.63
A2	2.65	1.92	1.66	2.87	2.56	2.33	2.27	2.62	3.56	3.05
A3	2.16	0.84	1.03	1.55	1.67	1.50	1.63	1.71	1.79	2.49
A4	3.22	3.17	3.40	3.66	3.75	3.43	3.33	3.05	2.98	2.08
A5	4.51	4.45	5.01	5.09	5.08	5.14	5.19	5.35	5.49	5.43

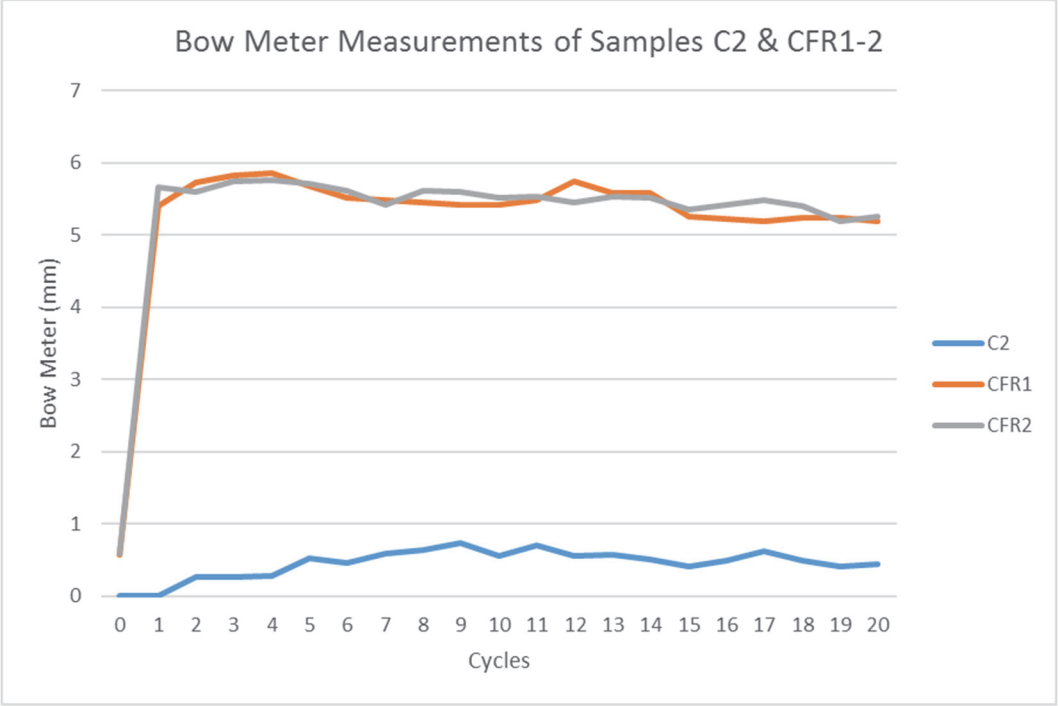
Standard Deviation of A1-5: 1.50 mm/m

	1	2	3	4	5	6	7	8	9	10
C2	0.00	1.13	1.18	1.22	2.32	2.02	2.58	2.82	3.19	2.41
CFR1	2.49	3.95	4.33	4.51	3.68	3.02	2.83	2.71	2.59	2.55
CFR2	2.61	2.34	2.97	3.04	2.84	2.36	1.57	2.39	2.28	1.99
	11	12	13	14	15	16	17	18	19	20
C2	3.06	2.42	2.50	2.19	1.80	2.14	2.69	2.14	1.76	1.96
CFR1	2.87	3.96	3.31	3.25	1.88	1.71	1.56	1.81	1.79	1.58
CFR2	2.05	1.69	2.01	1.95	1.28	1.54	1.80	1.43	0.53	0.80

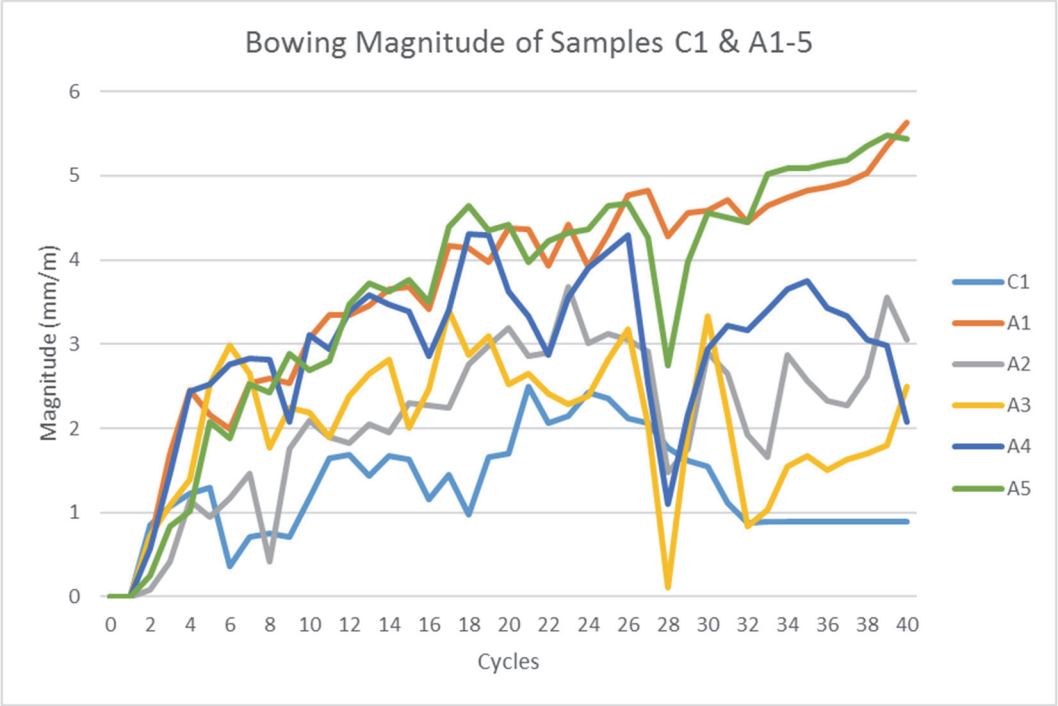
Standard Deviation of CFR1-2: 0.19 mm/m

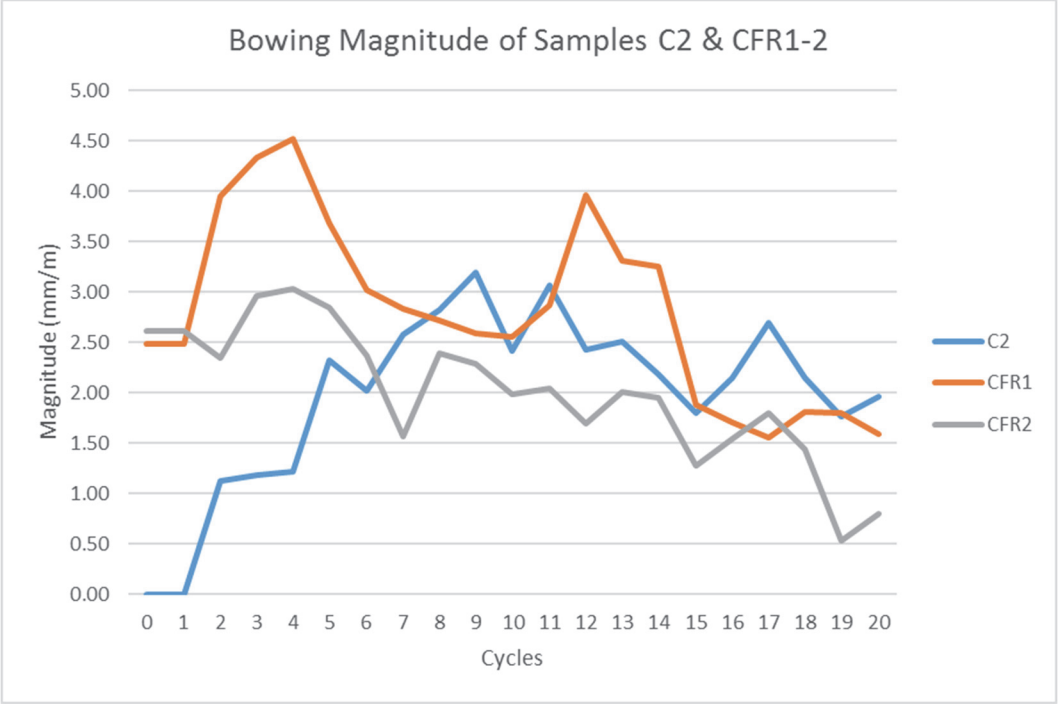
Graph of Bow Meter Measurements





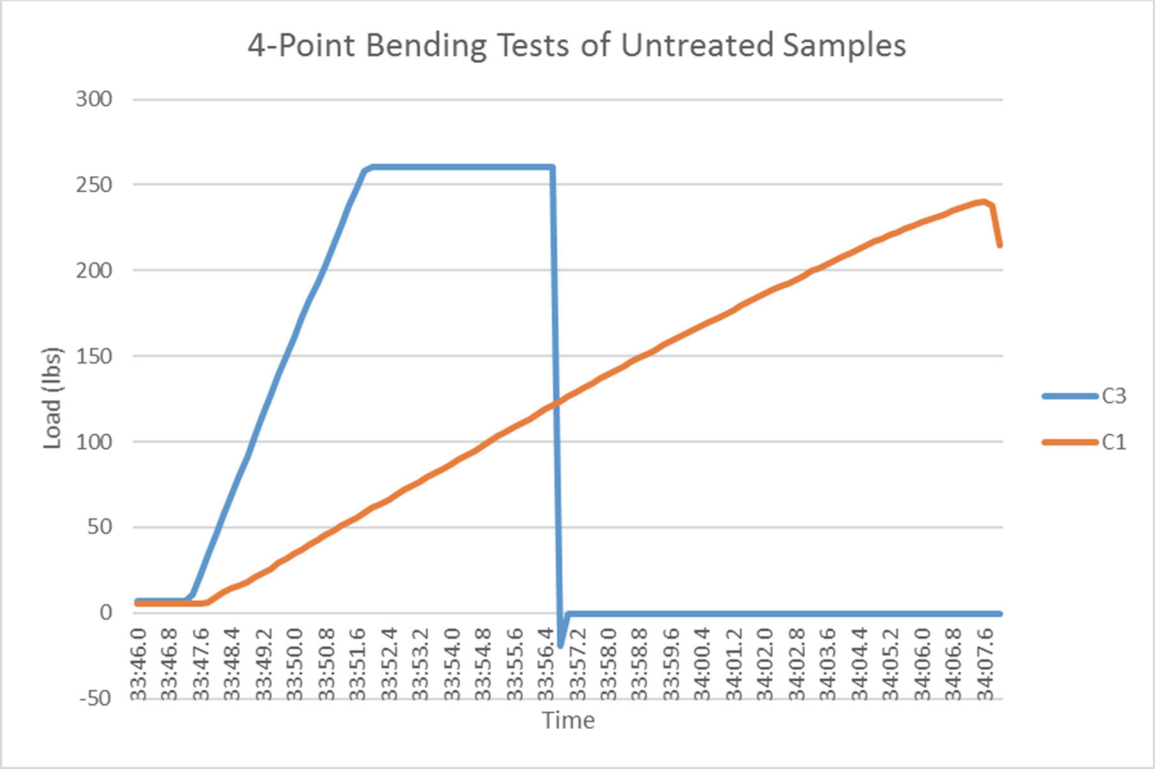
Graphs of Bowing Magnitude

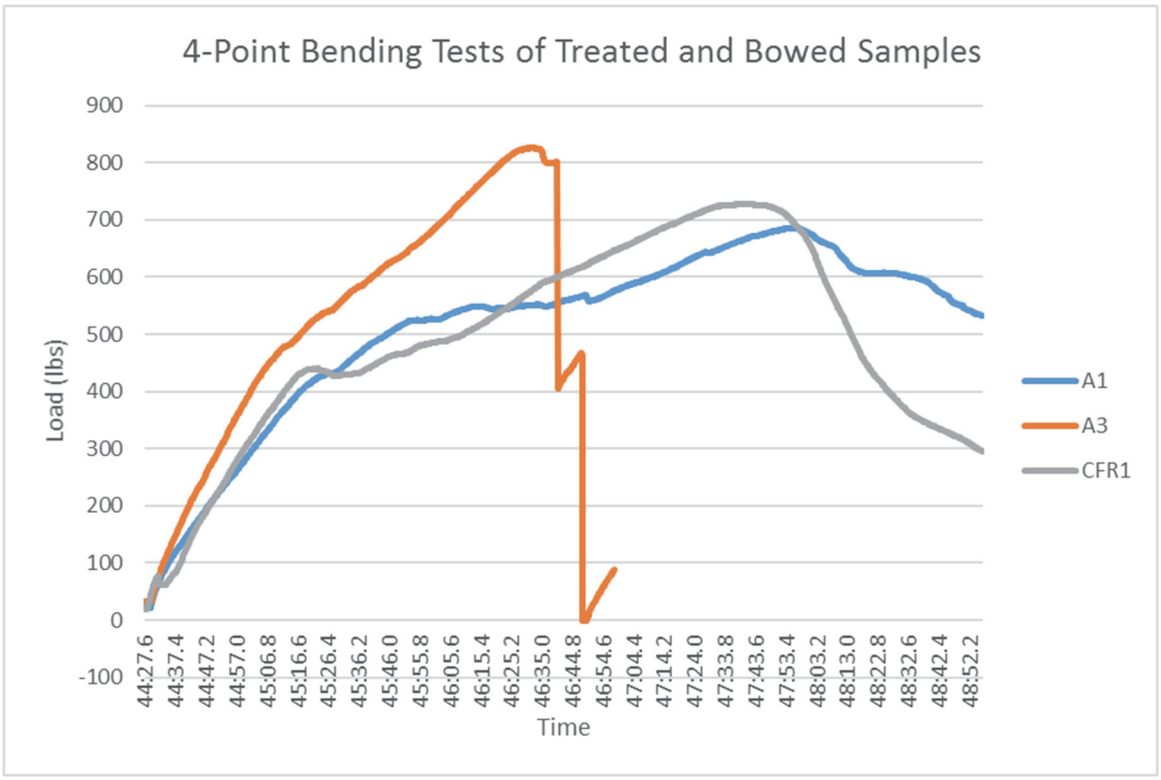


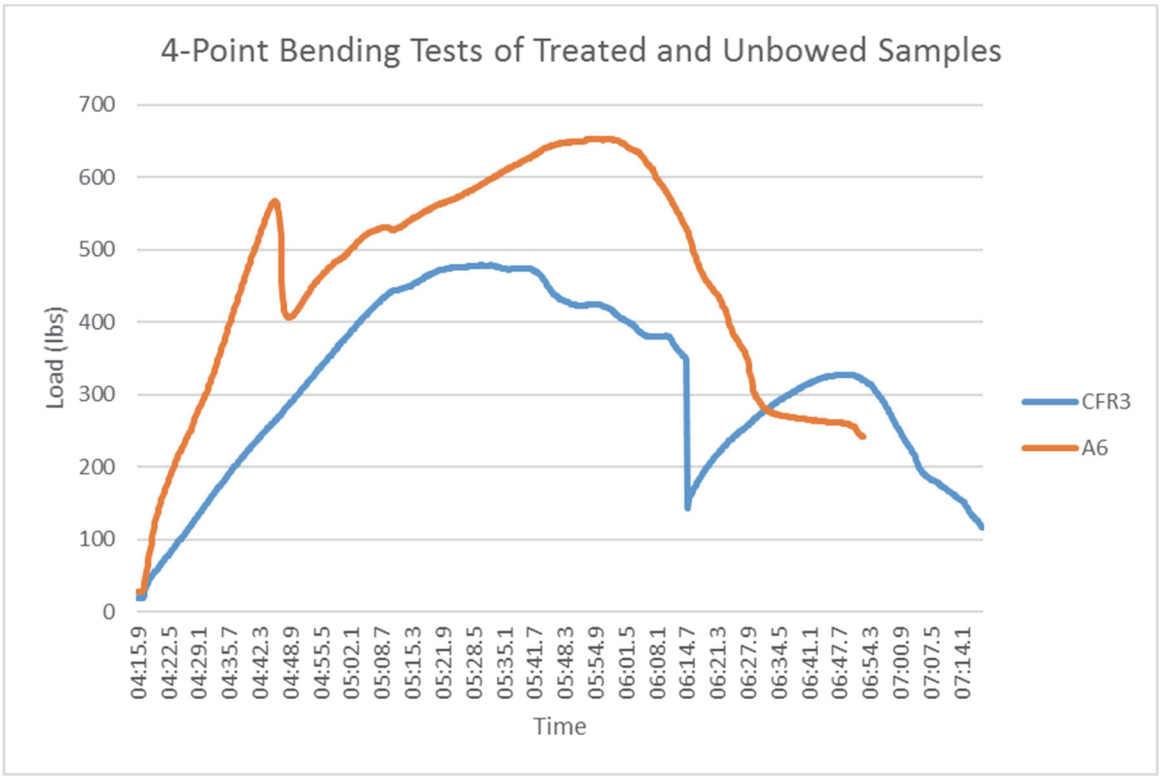


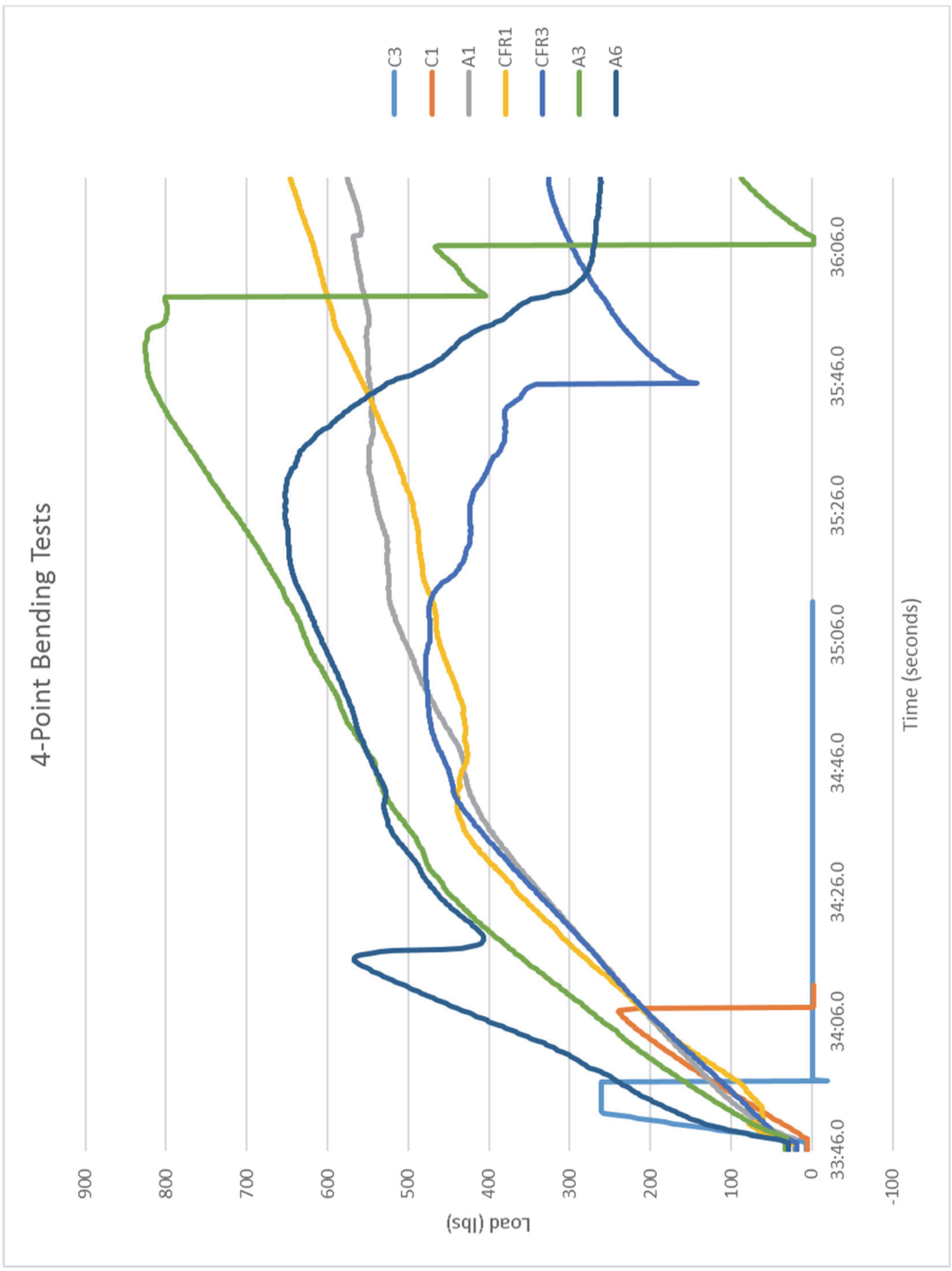
F: Flexural Strength Test Results

Samples	Maximum Load (lbs)	Flexural Strength (psi)
C1	239	1195
C3	260	1300
A1	680	2498
A3	825	3031
A6	652	2395
CFR1	718	2638
CFR3	475	1744

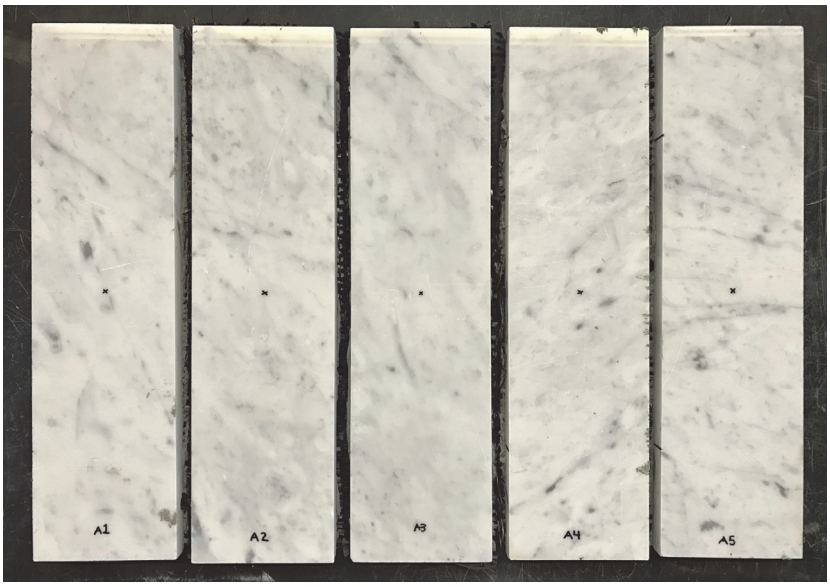



4-Point Bending Tests of Treated and Bowed Samples
900
800
700
600
500
400
300
200
100
0
-100
Load (lbs)
44:27.6
44:37.4
44:47.2
44:57.0
45:06.8
45:16.6
45:26.4
45:36.2
45:46.0
45:55.8
46:05.6
46:15.4
46:25.2
46:35.0
46:44.8
46:54.6
47:04.4
47:14.2
47:24.0
47:33.8
47:43.6
47:53.4
48:03.2
48:13.0
48:22.8
48:32.6
48:42.4
48:52.2
Time
A1
A3
CFR1

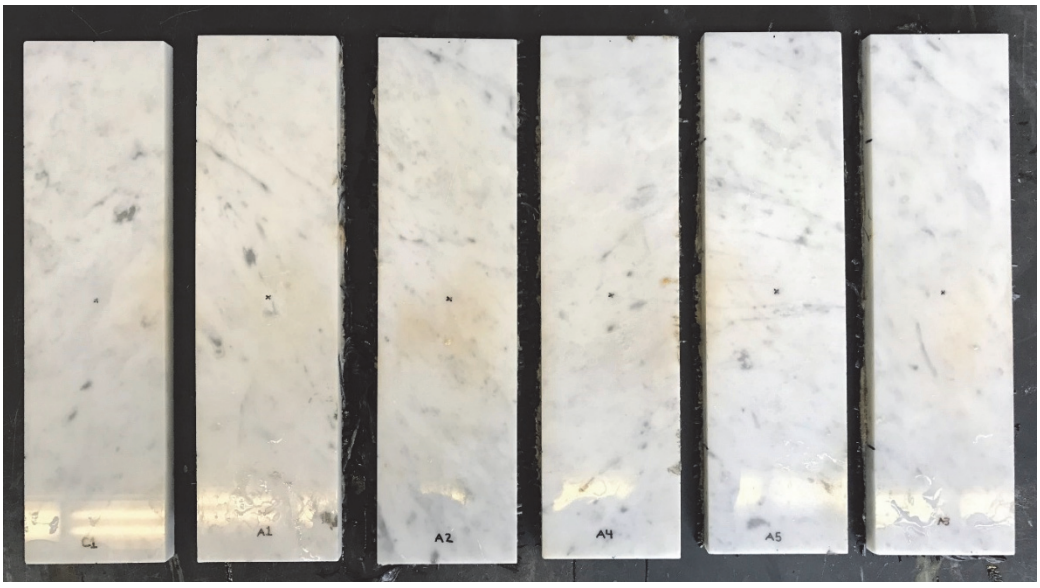

4-Point Bending Tests of Treated and Unbowed Samples
700
600
500
400
300
200
100
0
Load (lbs)
04:15.9
04:22.5
04:29.1
04:35.7
04:42.3
04:48.9
04:55.5
05:02.1
05:08.7
05:15.3
05:21.9
05:28.5
05:35.1
05:41.7
05:48.3
05:54.9
06:01.5
06:08.1
06:14.7
06:21.3
06:27.9
06:34.5
06:41.1
06:47.7
06:54.3
07:00.9
07:07.5
07:14.1
Time
CFR3
A6


4-Point Bending Tests
C3
C1
A1
CFR1
CFR3
A3
A6
Load (lbs)
900
800
700
600
500
400
300
200
100
0
-100
33:46.0
34:06.0
34:26.0
34:46.0
35:06.0
35:26.0
35:46.0
36:06.0
Time (seconds)

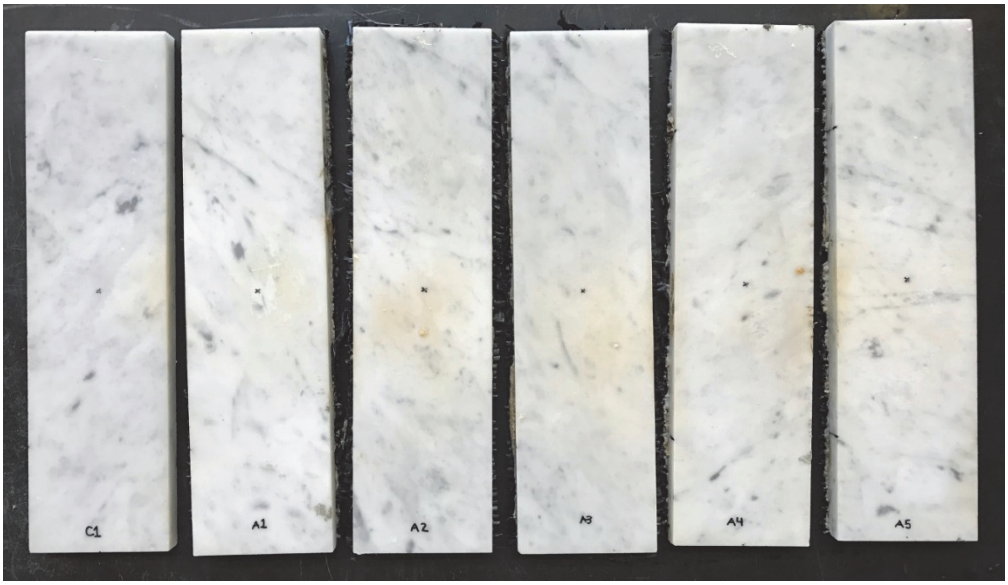
G: Visual Analysis of Marble Panels
Before Testing:



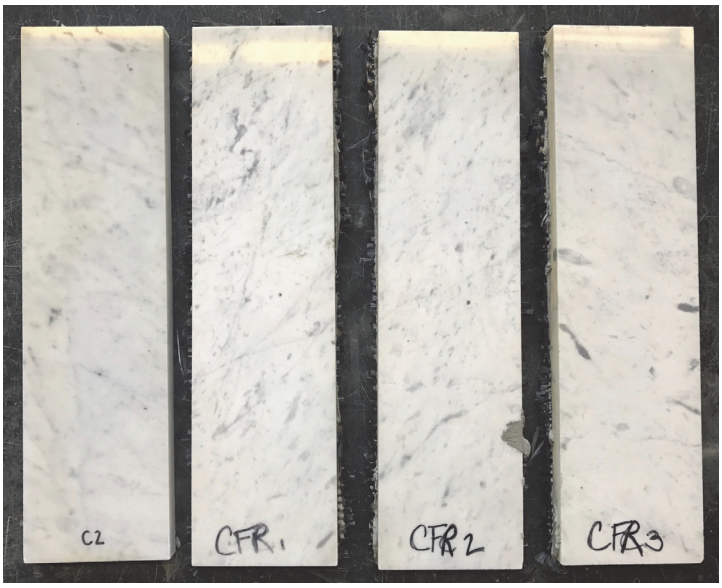
After 20 Cycles:



After 40 Cycles:

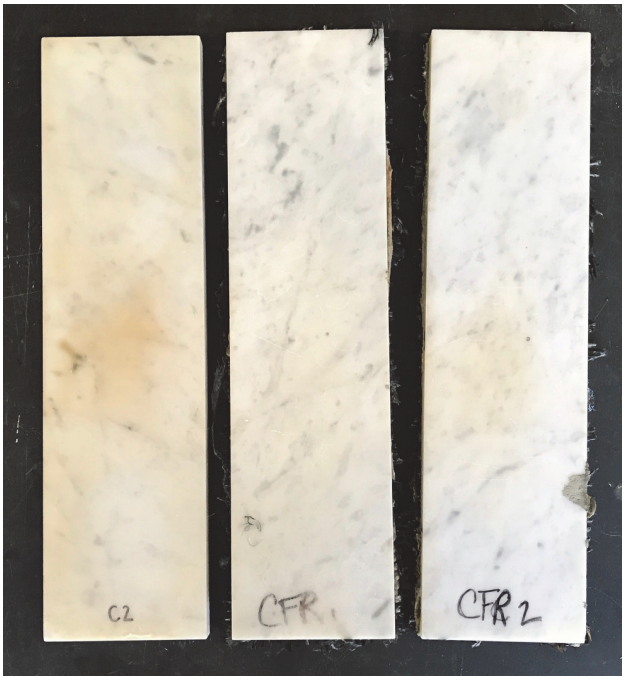


Before Testing:

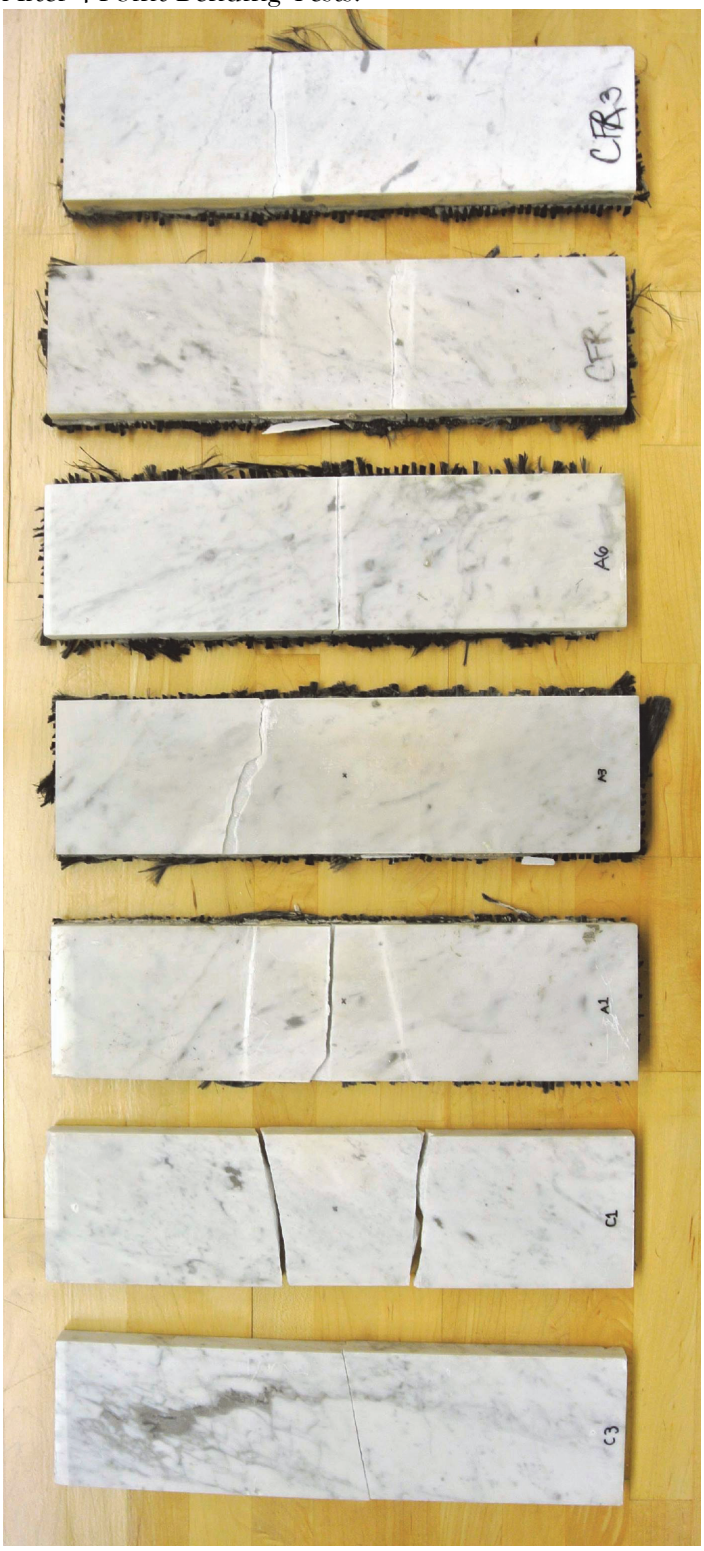


After 20 Cycles:

After 40 Cycles:



After 4-Point Bending Tests:



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